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Laboratory evaluation of surface treatments to asphaltic pavements in Mississippi

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LABORATORY EVALUATION OF SURFACE TREATMENTS TO ASPHALTIC PAVEMENTS IN MISSISSIPPI

By

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Chip and scrub seal treatments are one of the most common pavement preservation practices, however, no performance specifications exist in Mississippi. Review of literature has shown the treatment of cores being successful in reducing the viscosity of aged asphalt pavements. The purpose of this thesis is to provide a basis for performance based specifications for surface treatments in Mississippi. This thesis provides information pertaining to viscosity, moisture loss, and frosted marble analysis of emulsions and the effects of rejuvenation after application of emulsions to aged asphalt pavements which are vital to the performance of the surface treatment.

The objectives to this thesis are to determine and evaluate the effects of rejuvenation, frosted marble test, and moisture loss of emulsion applied to aged asphalt pavements. Results from these analysis' are favorable for developing or providing a basis for performance based specifications for surface treatments applied in Mississippi.

DEDICATION

I would like to dedicate this research to my Lord and Savior, Jesus Christ. I would also like to dedicate this research to my family, without their support and encouragement, none of this would be possible.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
A_1	First Acidaffins
A_2	Second Acidaffins
a	Inside Cross Sectional Area of Standpipe
A	Cross Sectional Area of Specimen
AA	Weight of Container, Rod, and Tin Foil
AFB	Air Force Base
AC	Asphalt Content
B	Initial Weight
C	Amount of Water Lost at Time Period
CC	Final Weight
CC	Weight of Binder in a Sample
CFS-2HP	Cationic Fast Set with High Polymer
CHFRS-2P	Cationic High Float Rapid Set with Polymer
CRS-2	Cationic Rapid Set
CRS-2P SBR	Cationic Rapid Set with Polymer (styrene butadiene rubber)
CRS-2P SBS	Cationic Rapid Set with Polymer (styrene butadiene styrene)
cP	Centipoise

D	Amount of Solids At Time Period
DD	Control Viscosity
DSR	Dynamic Shear Rheometer
F	Weight of Water Loss
FMT	Frosted Marble Test
FR	Frontage Road
G	Weight of Solids (25.5-*C)*
G	Grams of Emulsion at an Application Rate
H	1- Residue Value
HH	Viscosity of Fully Cured Emulsion
H_0	Null Hypothesis
H_a	Alternative Hypothesis
Hwy 45	Highway 45
Hg	Mercury
HMA	Hot Mix Asphalt
k	Permeability of Asphalt
KK	Amount of Emulsion in Core
LTTP	Long Term Pavement Performance
l	Thickness of Test Specimen
L_1	Hydraulic Head of Specimen at Lower Time
L_2	Hydraulic Head of Specimen at Upper Time
M	Maltenes
M_d	Mean Difference

MDOT	Mississippi Department of Transportation
MSU	Mississippi State University
NCAT	National Center for Asphalt Technology
NCCP	National Center for Pavement Preservation
NS	Non Scraped
P	Paraffins
Pa	Pascal
PASS-CR	Polymerized Asphalt Surface Sealer
PTSI	Paragon Technical Services Incorporated
PS	Provisional Standard
PVC	Polyvinyl Chloride
R	Residue Expressed as a Decimal
Roto-Vap	Rotational Vaporation
RTFO	Rolling Thin Film Oven Test
SCR	Scraped
SFS	Sabolt Furol Viscosity
SPS	Specific Pavement Study
SHRP	Strategic Highway Research Program
S27	Spindle Number 27
t	Time
TCE	Trichloroethylene
TNZ	Transit New Zealand
U	$1 - R$

U	Residue Value
USACE	United States Army Corps of Engineers
$V_{D(\%)}$	Percent Decrease in Viscosity
V_T	Treated Viscosity
V_U	Untreated Viscosity
wc_{LOSS}	Moisture Loss of Emulsion
X	Age in Months
XX	Amount of Emulsion scraped of a core
y	Relative Viscosity

CHAPTER I

INTRODUCTION

In past years, the development of the Interstate Highway System and supporting lower volume pavements was of primary concern, while preservation and maintenance were practically non-existent in the context of large scale activities. However, as the US highway system has aged, preservation and maintenance have become more of a priority. Pavement preservation is becoming increasingly important to civil infrastructures in which quality preservation requires advanced understanding of materials that can be measured by test methods that are related to in service performance (Howard et. al., 2009). In 2004, the *Office of Infrastructure* issued a memorandum making maintenance activities eligible for federal aid funding. Also in 2004, the *National Center for Pavement Preservation (NCPP)* was established and serves as many functions, with one being to compile technical research related to pavement preservation.

The highway system of Mississippi is fairly developed at present, but has only became so in recent years. Significant preventative and corrective measures will be required to preserve the Mississippi Highway System in future decades. The Mississippi Department of Transportation (*MDOT*) needs adequate tools to provide and create performance specifications for surface treatments. In present day the *MDOT* and many other Department of Transportation's (DOT's) are still posed with questions such as will a given preservation or maintenance treatment last through the winter rather than questions such as is this treatment an efficient use of resources. With current DOT budgets, difficult decisions appear inevitable, but targeted research can: (1) improve the effectiveness of a treatment; (2) improve decisions regarding when and how to apply treatments; and (3) relieve financial pressures that can in turn allow more efficient long term preservation and management practices. Current budgets prohibit hot-mix asphalt (HMA) overlays from being placed on low volume roads in some circumstances, so developing engineered seal treatments and corresponding analytical tools, test methods, and resulting performance specifications are extremely important.

Chip and scrub seals are common surface treatments that have been used primarily for maintenance purposes. In essence they are an asphalt emulsion sprayed onto the surface of an existing pavement that is subsequently covered with aggregates. Seal treatments in and of themselves have no additional structural capacity but can preserve the existing capacity and thus assist with traffic loading and corresponding potential for cracking. In addition, they can also restore or improve skid resistance, decrease permeability, and decrease viscosity of the pavement.

The primary purpose of the asphalt binder in the emulsion is to seal and soften the surface of the existing pavement while holding the surface aggregate in place. The surface aggregate is to protect the binder and provide adequate skid resistance and macro texture. The overall performance of the seal treatment relies on both components performing their intended functions. Quality pavement preservation requires advanced understanding of materials that can be measured by test methods that are related to in service performance. Material evaluation, selection, and understanding beyond basic specifications are critical for optimal performance. Chip and scrub seal emulsions must have sufficient fluidity to be applied uniformly while quickly coating the existing surface and cover aggregate. They must then quickly develop adhesion to retain aggregate for quick traffic opening, while maintaining flexibility over the long term for hot weather while not stiffening excessively so that cracking and early aggregate loss occurs. Though the use of ASTM D 946, ATSM D 3381 and ASTM D 244 provide useful information regarding the consistency of the materials and provide a means to communicate basic properties between users, however, these approaches do not necessarily provide insight into viscoelastic behavior, aging, interaction with existing pavement, and property thresholds are not directly associated with in service performance (Howard et.al. 2009).

According to Kuennen (2006), experience shows that spending $1 on pavement preservation before the point of rapid and precipitous deterioration can delay or eliminate spending $6 to $10 in future rehabilitation or reconstruction. Unfortunately, problems must develop prior to many agencies spending funds from their very limited budgets. A difficulty of pavement maintenance and preservation is to get individuals to give the matter due seriousness and respect. It is a highly complicated matter vital to the future of the nations highway system regardless of past practices or mindsets. Many parameters of surface treatments require improvement, notably optimal timing for treatment application, and performance based material/construction specifications.

1.1 Objectives of Study

The primary objective of this thesis is to determine the effects of chip and scurb seal surface treatments on aged asphalt concrete pavements for the potential use in performance based specifications for *MDOT*. Below is a list of objectives that this thesis will cover:

- Determine the effects of rejuvenation from a near surface treatment (i.e. emulsion treatment applied to the surface of an asphalt concrete core) using viscosity tests.

- Evaluate the effects of emulsion from a near surface treatment using the Frosted Marble Test.

- Assess moisture loss from an emulsion as it pertains to performance of emulsions used in chip and scrub seals.

1.2 Scope of Thesis

The scope of this thesis is to evaluate the effects of chip and scrub seal treatments on flexible pavements in the laboratory using the Frosted Marble Test (*FMT*) and viscosity testing of binder extracted and recovered near the pavement surface. Figure 1.1 illustrates how these two tests are used to evaluate the treatments. The *FMT* is used to evaluate the portion above the original pavement surface (denoted (1) in Figure 1.1) while viscosity testing is used to evaluate the portion of the treatment below the pavement surface (denoted (2) in Figure 1.1). Moisture loss testing was used throughout the study as appropriate.

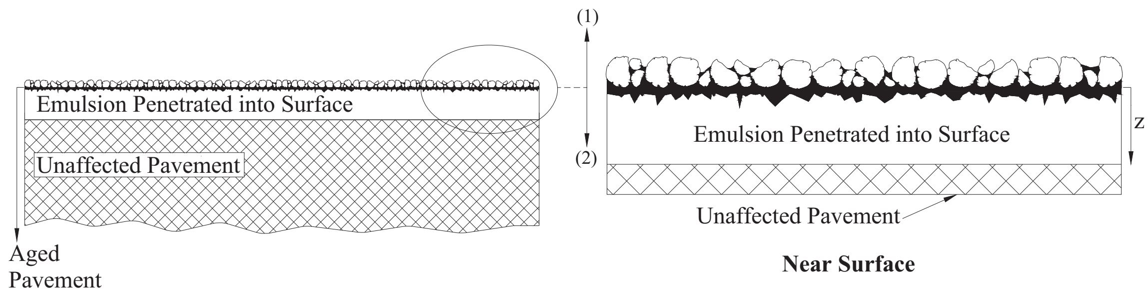


Figure 1.1   Detail of Pavement

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

A review of literature was performed to locate information in the areas of: rejuvenation; asphalt emulsions; aging and near surface treatments of flexible pavements; use of solvents; extraction and recovery procedures; use of viscosity testing to investigate near surface treatment behaviors; permeability; frosted marble testing; and moisture loss of emulsions in the laboratory. Practically zero applicable information was found related to moisture loss of emulsions. A limited number of performance oriented studies were found in terms of rejuvenation. The remainder of this chapter provides the information that was obtained during review of literature. The research focused on chip and scrub seals, while information from other seal treatments was incorporated as applicable.

2.2 Bituminous Materials Used for Surface Treatments

Due to the in service pavement conditions, petroleum based binders become brittle during the aging process, which leads to: (1) pitting and raveling of the surface; (2) shrinkage and brittleness cracking; and (3) spalling. Petroleum based asphalt binder consists of two main fractions: (1) *Asphaltenes*-hard and brittle component that is insoluble in Pentane and not affected by oxidation; and (2) *Maltenes*-oily and resinous in appearance and soluble in Pentane. *Asphaltenes* serve as the bodying agent, while the

Maltenes are the remainder of the asphalt material after asphaltenes precipitation. *Maltenes* consist of the constituents described as components in Eq. 2.1. *ASTM D 2006* provides test protocols to evaluate the Maltenes Distribution Ratio.

$$M = \frac{\mathrm{N} + \mathrm{A}_1}{\mathrm{P} + \mathrm{A}_2} \tag{2.1}$$

Where,

M = Maltenes (typically 0.4 to 1.4)

A_1 = First Acidaffins

A_2 = Second Acidaffins

P = Paraffins

Asphalt can be made more durable by adding those components it lacks (or those that have increased) to restore its original state prior to weathering (i.e. rejuvenate the asphalt). A conceptual key to rejuvenation is to properly adjust the oil/resins ratio. Physical keys to effective rejuvenation include: (1) emulsion penetration of adequate distance readily and rapidly into the asphalt (6.3 to 12.5 mm is commonly referred to as a typical upper end of penetration depths); (2) sufficient wetting of the existing asphalt; (3) sufficient combining with the existing asphalt; (4) no adverse affects with regards to adhesion, asphalt binder films, aggregate structure, or overall stability; (5) selection of an appropriate carrier (e.g. water); and (6) decreasing the viscosity of the existing asphalt.

Hot asphalt, coal tar, and asphalt emulsions are examples of surface treatment products that have been used on flexible pavements. Rejuvenators are diluted water-based emulsions of oils designed to penetrate into the existing asphalt cement and modify and improve existing chemical and rheological properties (King and King, 2008). Many agencies have resorted to the use of asphalt rejuvenators as an alternative to revive aging and brittle asphalt pavements (Boyer, 2000). Rejuventating a pavement can have the potential of extending the life of a pavement for several years, resurrect an aged pavement as it penetrates, and improve or restore the malteness/asphalteness balance of the pavement, and provide a reasonable measure of the ability to improve a pavements durability.

The CRS-2 emulsion (or polymer modified emulsion with CRS-2 as the base) is one of the most commonly used family of emulsions for surface treatments in the United States. A technical representative from Paragon Technical Services Inc. (PTSI) stated that the CRS-2P SBR emulsion is a CRS-2 emulsion polymerized with latex and sulfur. This emulsion is polymerized with styrene butadiene rubber which is used to form a "honeycomb" structure in the emulsion, thus providing its strength and rejuvenation properties. CRS-2P SBS emulsion is produced by polymerizing CRS-2 emulsion with styrene butadiene styrene, producing a different form of polymer emulsion. Both are referred to generally as CRS-2P.

PASS-CR, CHFRS-2P, CFS-2HP, and Road Armor emulsions are proprietary products of the CRS-2P emulsion. The PASS-CR emulsion is primarily used in scrub seal construction (Ergon Asphalt and Emulsions, 2009). This emulsion is primarily used for mass crack sealing on routes that have been distressed beyond the ability of a conventional surface treatment to correct which adds flexibility, toughness, and durability to the surface and restores the asphalteness and malteness in the pavement. The CHFRS-2P emulsion is a high float emulsion stated to provide excellent chip retention and the ability to provide a quick return to traffic.

Boyer (2000) concluded that an asphalt rejuvenator in the form of an emulsion offers three beneficial reactions: (1) increases penetration values and lowers the viscosity of the asphalt binder in the top portion of the surface layer, which extends the pavement's life cycle; (2) seals the pavement against intrusion of air and water, thereby slowing oxidation, preventing stripping and raveling and protects the pavement in-depth; and (3) increases the durability of the asphalt binder in the top portion of the pavement by improving the balance of chemical fractions of the asphalt binder.

Aging and oxidation are leading components in the deterioration of flexible pavements. Boyer (2000) states that the cementing agent in an asphalt pavement represents the component that experiences premature hardening as a result of oxidation causing deterioration of a flexible pavement. Harder emulsion residues in sealer products have much less impact on the rheology of surface layers, but they do retard oxidation in the flexible pavement (King and King, 2008). Coons and Wright (1968) confirmed that there was a significant effect due to age and depth on aging of flexible pavements.

2.3 Design and Performance of Surface Treatments

Aggregate loss and bleeding are common surface treatment failure modes. ASTM D 1369-84 provides typical application rates of emulsion used for surface treatments and suggests corrections for various conditions. The document is useful, but does not provide all the information needed for adequate design of a seal treatment in many cases. In NCHRP Synthesis 342 (Gransberg and James, 2005), it was found that often agencies merely use the rates from the previous year's chip seal program as a means to quantify the amount of binder to apply. The application rates used in practice are dependent on the condition of the pavement and past experiences. Holmgreen et. al (1985) concluded that the modified Kearby method used in Texas included a “hunger factor” to characterize the amount of oxidation or flushing that is present on the existing surface which leads to an incremental increase/decrease in the binder application rate to account for binder absorption in the surface.

Performance specifications are defined as a measurement of “how the finished product should perform over time” (Chamberlain 1995). TNZ P/17 (2002) is an example in that it states that texture depth after 12 months of service is the most accurate indication of performance of a chip seal.

Boyer (2000) stated that rejuvenator products perform differently among themselves in a given environment and differently within themselves in changing environments. Therefore, a given application rate in most projects does not insure a desired end product and further restrictions govern application rates to avoid unacceptable anti-skid, softness and/or performance characteristics. Caution should be used for determining application rates in order to improve or restore the viscous properties of the asphalt binder. Requiring the rejuvenator to achieve a given measure of standard penetration or measure of viscosity should insure a more satisfactory result than simply specifying a given rate of application; especially prior to fully developed performance specification. A performance specification was used at Kincheloe AFB, Michigan, in which it called for a 30 percent increase in the penetration of the asphalt in the top 6.3 mm of the pavement 60 days subsequent to application (Boyer, 2000).

Emulsion infiltration is also important to the success of a surface treatment. This process allows the treatment to enter an asphalt pavement and restore it properties. King and King (2000) indicated laboratory permeability tests on field cores may be a better measure for predicting emulsion infiltration, and for evaluating the finished seal's ability to keep water out of the pavement. Furthermore, fog seal emulsions rarely infiltrate into the pavement more than 12.5 mm. Sealers and rejuvenators can be used on any asphalt pavement that has sufficient permeability to allow emulsion infiltration, but traffic should be controlled until the seals have fully cured and friction numbers are fully restored.

2.4 Solvents Used for Extraction and Recovery

Selection of the solvents for asphalt extraction was a key component of this research. The solvents used in extracting the asphalt binder from a mix are important in determining the properties of the recovered binder. Burr et al. (1994) reported up to 50% softening of asphalts in solutions while using a modified Roto-vaporation recovery technique. Rates of reaction were shown to increase a considerable amount as a function of oil bath temperature (102 to 149 C were investigated), and were shown to slow in a solvent of toluene with 15% ethanol. It was recommended to exercise care with asphalts in dilute solutions for extended periods of time at temperatures exceeding 93 C, especially polar solvents such as TCE/ethanol. Solvent softening was reported to vary widely with asphalt source and solvent type. Using toluene/ethanol as the solvent resulted softening in the most severe conditions (high oil bath temperature with low asphalt concentration). Toluene/ethanol solvents were recommended, but it should be noted they are not as efficient at removing absorbed material from aggregate. Asphalts and maltenes undergo softening reactions in dilute solutions at high temperatures and low asphalt concentrations. Solvent hardening was said to occur at high asphalt concentrations in diluted solutions. Up to 50% viscosity decrease was said to occur from softening, while up to 15% viscosity decrease was mentioned due to hardening. Using toluene/ethanol with oil bath temperatures below 110 C with solutions having concentrations exceeding 0.15 g/ml was recommended.

Burr et al. (1993) provides excellent discussion of the history of asphalt extraction and recovery that dates back over 100 years. Highlights include centrifuge extraction leaving 2 to 4% of asphalt on aggregate when trichloroethylene (TCE) is used. Centrifuge extraction using 15% ethanol in the TCE reduces the percent asphalt remaining on the aggregate by approximately half. Solvent extraction using rotary evaporation has been reported to leave residual solvent. This was said to be problematic since low solvent concentrations (e.g. 0.2%) can cause physical property testing errors. Modification of ASTM D 2172 Method A (centrifuge) with toluene and for the late washes 85% toluene/15% ethanol by volume was comparable to the procedure developed for Strategic Highway Research Program (SHRP). More solvent was used than in the standard procedure and all washes were collected in one container until extraction was complete. The researchers used a very high number of washes (eleven) versus many standard practices (e.g. 4 to 6 washes). Previous work by the same researchers reported tank asphalts that were dissolved and recovered immediately hardened between 10 to 40 percent (Burr et al. 1990).

Cipione et al. (1991) cites coefficients of variation from nationwide asphalt extraction to be 25% as early as 1989. The work focused on removal of “hard-to-remove material” (i.e. strongly adsorbed residual asphalt material). Results indicated TCE with

15% ethanol was superior for this purpose and concluded that many solvents do not remove the bulk of the asphalt binder.

Burr et. al (1991) stated that asphalt recoveries by the Abson and Roto-vap methods were performed at various temperatures and for several asphalt viscosities from tank, oven aged, and solvent exposed asphalt to evaluate the effectiveness of the procedures and operating parameters. It was found that small amounts of solvent cause significant decreases in viscosity, and present recovery methods do not remove solvent adequately. High viscosities and larger *HMA* samples hinder solvent removal rates in the Abson Method. Asphalt hardens significantly on extended exposure to TCE at both 93 C and 127 C however, removal at a reduced temperature through use of a vacuum in the early stages can inhibit it.

In Burr et. al. (1991), the volatiles loss from virgin or unaged tank asphalts during solvent removal was shown to produce 7-10% hardening of the original asphalt viscosity. RTFO asphalts do not exhibit this hardening, apparently because of the loss of volatiles during aging. The same asphalts show hardening from 10 – 40 % on contact with TCE and subsequent solvent removal. Short times and moderate temperature for incubation of the asphalt with solvent produce little hardening; extended times at elevated temperature can produce significant hardening.

In Burr et. al. (1991), experiments were conducted with the Abson and Roto-vap solvent removal methods for the purpose of evaluating their effectiveness in removing solvents. The Abson method, taken to its standard recovery time, can leave enough solvent to produce significant softening, especially for larger quantities of recovered material and for hardened asphalts such as those obtained from aged pavement cores.

Increasing the temperature of the solvent removal and the recovery time can reduce this residual solvent concentration, although the previously mentioned solvent hardening effects must be considered. The Roto-vap method appears to be less consistent and less reproducible than the Abson method, but it may have some advantages for solvent removal. For the Abson procedure at 163 C a minimum recovery time after the last drop is about 25 minutes and the Roto-vap, 15 minutes past the last drop is adequate.

2.5 Penetration and Viscosity Changes from Applied Surface Treatments

Several viscosity tests have been developed and used for determining the effects of emulsion applied treatments on flexible pavements. These test include kinematic, vacuum capillary, rotational, and Saybolt viscosity.

AASHTO T 201 (ASTM D 2170) measures the kinematic viscosity of asphalt binder. Time is measured for volume of liquid to flow through glass capillary viscometer. The test is conducted at 60 C and 135 C with units of centistokes (mm^2/s). ASTM D 445 is similar to that of ASTM D 2170.

AASHTO T 202 (ASTM 2171) measures the viscosity of asphalt binder through the vacuum capillary viscometers. Time is measured for volume of liquid to flow through a capillary tube by means of a vacuum. This test is conducted at 60 C with units of poise (Pa*s).

AASHTO T 316 measures the viscosity of recovered asphalt binder through a rotational viscometer. This test administers a specimen at a constant temperature where submerged cylindrical spindle is rotated at a constant speed which measures the relative resistance to rotation. This test is conducted at 60 to 200 C with units of poise (Pa*s).

AASHTO T 72 (ASTM 88) measures the viscosity of recovered asphalt binder through the Saybolt viscosity procedure. Time is measured for volume of liquid to flow through an orifice at controlled conditions. This test is a special procedure for determining the viscosity of waxy products. This test is conducted at 21 to 99 C with units of second (s).

Rejuvenation effects due to emulsions (i.e. reduction of viscosity) often last for a period of time, followed by a subsequent increase that may or may not exceed the viscosity of the original pavement. In other words, the rejuvenation may be temporary. Rejuvenators placed in the form of fog seals appear to be the most common application where near surface materials are extracted and the penetration or viscosity of recovered binder evaluated. This is significant in multiple contexts, one of which is that application rates in these situations are less than for chip and/or scrub seals where not all the bituminous material is intended to penetrate into the pavement. As an example, application rates of 0.18 to 0.91 L/m^2 were allowed with tolerances of $\pm$ 5% from the intended value in (Corps of Engineers 1983).

A method of evaluating effects of rejuvenators and asphalt emulsions on surface treatments applied to in-service flexible pavements is viscosity reduction. Corps of Engineers (1983) required a 40% decrease in viscosity of the upper 9.5 mm of the pavement from rejuvenation, as defined by Eq (2.2). This remains unchanged (Corps of Engineers 2006). Composite samples were used in determination of all Eq (2.1) properties.

$$V_{D\%} = \frac{V_U - V_T}{V_U}(100) \tag{2.2}$$

Where,

$V_{D\%}$ = decrease in viscosity

V_U = untreated viscosity

V_T = treated viscosity

Traxler and Schweyer (1936) provided the first conclusive statements regarding viscosity increase with time while temperature was held constant. Simpson et. al. (1959) found that, in general, the asphalt in the top 6.3 mm of a pavement had a higher viscosity than the rest of the pavement, including both the surface and base. A microviscometer was used to study 32 and 35 month old cores. At depths lower than 12.5 mm, there was less change in the top 12.5 mm. Higher viscosities were sometimes encountered in the top of the base course indicating that appreciable hardening occurred between the laying of base and surface coarses.

One of the first notable studies of viscosity of pavements with depth was Coons and Wright (1968). Cores of pavements varying in age from 1 to 13 years were obtained from Georgia and sliced parallel to the pavement surface. The binder was recovered and tested to determine absolute viscosity related to depth, age, and original viscosity. All testing was performed on asphalt with no surface treatments.

The parallel slice was first dried for 20 minutes at 121.1 C, broken into small pieces, returned to the oven for 10 minutes, and then the binder was extracted with reagent grade benzene. Each 6.3 mm thick 150 mm diameter slice was extracted separately. The total mass (aggregate and binder) of the slices was on the order of 275 g. The saw blade thickness was 3.2 mm thick, so a complete depth profile was not obtained.

Viscosity versus depth profiles showed the greatest hardening to occur in the top 12.5 mm of the pavement. The top slices (0 to 6.3 mm pavement depth) had an average viscosity that was approximately 50% greater than that of the second depth of slices (9.5 to 15.9 mm pavement depth). Investigation within the top slice indicated most of the hardening occurred in a layer less than 4.8 mm thick.

Relative viscosity was also investigated by Coons and Wright (1968) and is defined as the viscosity after a period of time divided by the original viscosity. The top two slices both hardened noticeably with time, while the remaining layers did not. Additionally, the hardening of the top layer with time was characterized by Eq. 2.3. After approximately 10 years, the relative viscosity could be expected to be around 19 according to Eq. 2.3.

$$X = e^{(y+1.07)/4.21} \tag{2.3}$$

Where,

X = age in months

y = relative viscosity

Boyer (2000) concluded that satisfactory performance guidelines or targets should be based on the capability of the material to decrease the viscosity and increase the penetration value of the asphalt binder. In the case of pavements less than 2 years old, the minimum viscosity reduction of 20 percent and minimum penetration increase of 10 percent were reported. For asphalt pavements more than 2 years old, the minimum viscosity reduction of 40 percent and minimum penetration increase of 20 percent were reported. Testing was recommended to be performed on recovered asphalt binder from the pavement to a depth of 9.5 mm.

Sholar et. al. (2000) performed a study in Florida, evaluating sealer-rejuvenator treatments. This study involved the use of an in-service shoulder of I-295 using a coal tar product. The purpose of this was to determine if the shoulder would maintain a longer useful life than the mainline roadway. On the day of application, six cores were obtained at random locations within the test section and the top 12.5 to 19 mm were sliced and used to obtain pretreatment viscosity of the recovered binder from cores. Cores were then taken 29 days after treatment, the top 12.5 to 19 mm sliced, and viscosity tests performed on recovered binder.

It was found through this study that there was no significant change between the before treatment asphalt binder viscosity (106,846 Poises) and the asphalt binder 29 days after treatment (106,329 Poises). The results from this research indicate that the use of coal tar does not significantly reduce the viscosity of the pavement.

Fog sealed pavement sites were tested once per year for two years and extracted binder properties were compared to untreated sections of the same sites using paired *t*-testing (Prapaitrakul et al. 2008). Effects were restricted to the top 6.3 mm of the pavement. Slow setting, medium setting hard residual emulsion polymer modified emulsion, and coal tar sealers were tested with application rates from 0.18 to 0.72 L/m^2. It was stated that fog seals with rejuvenators have been used for maintenance and preservation activities, but evidence to date is not sufficient to prove that sealants rejuvenate in-place binders. Three 6.3 mm layers were sliced parallel to the pavement surface. A solvent of 15% Ethanol and 85% Toluene by volume was used for extraction via 3 or 4 washes of 20 minutes each. Recovery was performed with a Roto-vap apparatus and the result was practically no asphalt in the aggregate. Three 6.3 mm slices were obtained from the top 25.4 mm of the pavement. The result was that the fog seal effects were noticeable in the top 6.3 mm, but not at other depths providing evidence of approximately 6.3 mm penetration.

Brown and Johnson (1976) noted that full documentation of rejuvenation effectiveness was not available some three decades ago; a similar environment exists in present day. Additionally, what identifies a pavement as capable of rejuvenation was not (and still is not) fully defined. Brown and Johnson (1976) undertook a comprehensive investigation of rejuvenation capability of five materials (Table 2.1) at three airfields where decrease in viscosity or increase in penetration were the basis for evaluating rejuvenation.

Table 2.1

Properties of Rejuvenators Used by Brown and Johnson (1976)

Material	**Type**	**Saybolt [1] Viscosity (s)**	**Residue (%)[2]**	**Residue Viscosity (Poises)[3]**
A: Koppers BPR	Tar Products	22	51	0.70
B: Reclamite	Asphalt Emulsion	22	67	1.47
C: Petroset	Asphalt Emulsion	22	62	14.27
D: Gilsabind	Cutback Asphalt	42	20	---
E: SS-1	Asphalt Emulsion	89	65	---

1: Saybolt viscosity at 25 C on as received rejuvenator.
2: Material (A) performed with ASTM D 20, (B, C, and E) with ASTM D 244, and (E) with ASTM D 402.
3: Residue viscosity performed at 60 C according to ASTM D 2170.

The desire of the researchers was to test three airfields from different climates approximately ten years old that were free of maintenance, unfortunately almost all pavements that were ten years old or more had been maintained with some sort of surface treatment. The taxiways of three air force bases were ultimately tested: Eglin in Florida, Malmstrom in Montana, and Williams in Arizona. Eglin had many longitudinal and transverse cracks up to 12.5 mm and had a surface asphalt content of 5.8%; Malmstrom had a slurry seal placed several years before and had a surface asphalt content of 6.3%; and Williams had been treated two or three times previously with a diluted fog seal and had a surface asphalt content of 5.3%.

A portion of the study was to develop laboratory procedures to accelerate the oxidation of asphalts for evaluation of rejuvenators. Using penetration tests and laboratory aged asphalt, materials A, B, and C were able to soften the laboratory aged asphalt. The majority of the effort was related to testing of the aforementioned airfields.

The optimum rejuvenator application rate was determined with 0.9 meter square patches with application rates of 0.23, 0.46, and 0.69 L/m^2. The rate was selected as the amount that would entirely absorb into the surface in 24 hr, or if the material did not penetrate into the pavement the minimum amount needed to completely cover the surface was selected as the application rate. At each airfield the rejuvenator was applied at the optimum rate and at half of the optimum rate.

Penetration (ASTM D 5) and viscosity (ASTM D 2170 with values reported in centistokes) tests were performed on cores taken at 0.07, 6, 12, 24, and 36 months by slicing the top 9.5 mm of the pavement and recovering the binder from the 9.5 mm slice. Viscosity was reported to be a better indicator of rejuvenation than penetration. At each airfield treated viscosity was expressed as a percentage of untreated viscosity of the control sections at 135 C (other temperatures paralled these behaviors). Results of the work of Brown and Johnson (1976) applicable to the current effort are provided in Table

2.2. As seen, the effect of rejuvenation was varied with two of the materials stiffening the aged asphalt at 0.07 and 36 months. Materials A, B, and C softened the binder at 0.07 and 36 months, though the extent of softening decreased with time. Brown and Johnson (1976) recommended rejuvenators at the first sign of pavement deterioration such as cracking, raveling, and/or loss of fines from the surface.

Table 2.2

Select Test Results of Brown and Johnson (1976)

Material	**Application Rate (L/m^2)**	**Percent of Control Viscosity (0.07 months)**	**Percent of Control Viscosity (36 months)**
A	0.27 to 0.54	17 to 42	60 to 66
B	0.27 to 0.45	38 to 84	67 to 96
C	0.27 to 0.45	61 to 81	95 to 99
D	0.27	146 to 178	138 to 164
E	0.27	107 to 111	132 to 146

The current US Army Corps of Engineers (USACE) unified facilities guide specification (UFGS) for Bituminous Rejuvenation (UFGS 02787) requires that the asphalt cement recovered from the upper 9.5 mm of a pavement shall have a decrease in viscosity of at least 40% with respect to untreated material. The guide is heavily based on the work of Brown and Johnson (1976) discussed earlier in this section. Shoenberger (2003) continued the work of Brown and Johnson (1976) by focusing on propriety rejuvenator and sealer materials for airfield pavements. The premise of the work was that performance based requirements were preferred over material property specifications.

Shoenberger (2003) evaluated eleven rejuvenator materials and five seal coat materials at two airfields: MacDill in Florida representative of hot and humid conditions and McGuire in New Jersey representative of cold and humid conditions. Eight of the rejuvenator materials were coal-tar based, while three of the rejuvenator materials were petroleum based. Properties of select materials are shown in Table 2.3.

Table 2.3

Properties of Rejuvenators (Shoenberger 2003)

			Application Rate		Viscosity[2]	
Type	**Product**	**Res[1]**	**MacDill (L/m^2)**	**McGuire (L/m^2)**	**Saybolt (s)**	**Brookfield (cP)**
Coal-Tar	BCR	---	0.23	0.23	171	130
	CBRT-SO	---	0.30	0.25	---	---
	RejuvaSeal	---	0.23	0.23 to 0.27	31	---
Petroleum	APR-100	84	0.27	0.31	82	---
	GSB	63	0.54 to 0.63	0.61 to 0.91	159	670
	Reclamite	61	0.23 to 0.45	0.27 to 0.68	31	153

1: Residue from ASTM D 244
2: Viscosity tested at 25 to 26 C and as obtained with no dilution

Cores (150 mm diameter) were taken pre and post treatment, with post treatment cores taken at one month and twelve months. Cores were not taken until one month to allow evaporation of excess volatile materials and for rejuvenation to occur. Cores were taken from areas with minimal cracking or surface distresses.

To investigate effect of the coating on overall rejuvenation performance, the top 1 mm was removed and discarded and subsequently the next 9 mm removed, the binder extracted, and testing performed. Other cores had the entire 10 mm removed, the binder extracted, and testing performed. Removal of 1 mm consistently was reported to be difficult by Shoenberger (2003). Three cores were required per test. Kinematic viscosity testing was performed according to ASTM D 2170 at 135 C, and the results can be seen in Table 2.4.

Table 2.4

Viscosity Results from Rejuvenators (Shoenberger 2003)

$V_{D\%}$	MacDill Airfield			McGuire Airfield	
Thickness (mm)	**10**	**10**	**9**	**10**	**9**
Months Sealed	**1**	**12**	**12**	**1**	**1**
BCR	32	63	56	49	---
CBRT-SO	48	56	---	59	55
RejuvaSeal	76	---	---	14	57
APR-100	75	35	---	26	41
GSB Emulsion	36	16	4	43	14
Reclamite	62	57	60	18	57

Note: Thickness of 10 mm was top 10 mm and 9 mm had top 1 mm removed.

Penetration tests did not show a consistent pattern for either MacDill or McGuire airfield, while viscosity tests at one month and twelve months showed a lowering of viscosity at both airfields as evidenced by the data in Table 2.4. Removal of the top 1 mm appeared to affect test results, but the effect was not reported to be conclusive by Shoenberger (2003). All rejuvenator materials reduced binder viscosity, but the extent of the reduction varied. Sample cores were arbitrarily obtained within taxiways, and as such are an indication of behavior that does not necessarily account for variability of untreated viscosity.

Shoenberger (2003) also performed dynamic shear rheometer (DSR) testing to evaluate effectiveness, though did not recommend its use. Provided DSR testing was used, the phase angle was recommended over the shear modulas. Evaluation of the sections over several years was recommended, alongside development of a test method for determining effects of a rejuvenator.

2.6 Frosted Marble Testing

The purpose of a chip seal is to achieve a high adhesion (i.e. high aggregate retention strength) followed by a leveling off period. The *FMT* is not a common test method however, limited groups use the test for internal information and equivalent purposes (Howard et al. 2009). C.R. Benedict developed the original test method (Benedict, 1990).

Guiles (1995) implemented the *FMT* but modified the curing regime to capture early torque data that could indicate the ability to withstand brooming actions and early traffic. The test was also used for assisting in the determination of the minimum amount of emulsifier needed to produce a stable CRS-2P emulsion. It was asserted that no such test had been performed for this purpose beforehand. For this test, CRS-2 and three versions of CRS-2P with 3% polymer in emulsion residue were tested in which testing was similar to Benedict's with the exception of the curing protocol and test repetition. The curing protocol provided 4 data points: 2, 4, 6 hrs of 37.8 C and 16 hrs of ambient conditions. At 6 hours, emulsion leveled off and was said to indicate full curing. Thirty tests were averaged and recorded as the chip retention strength. The polymer appeared to soften this type of material or retard its ability for early strength gain. The study reported polymers did not increase set time during the first 6 hours, and that polymers decreased set at 2 hours. CRS-2P had significantly improved properties relative to the CRS-2 at 16 hours.

Howard and Baumgardner (2009) summarize the original tested method for the *FMT* that involved a study with US Highway 84 (US 84) project near Brookhaven, MS. The primary objective for US 84 was to establish an approved products list of polymer modified CRS-2 emulsions using primary evaluation considerations that were to evaluate early chip retention set forth by *MDOT* internal memorandums.

The *FMT* device is a modified cohesion tester with a 50 mm hooked foot and a torque wrench used to dislodge a 14.3 mm acid etched glass bead. The asphalt emulsion is contained in a trough on a flat steel tray at an application rate of 1.5 L/m^2. Five glass beads are applied to each trough (3 troughs per tray). The original test was performed after three curing conditions at an air pressure of 200 kPa in which was used to raise and lower the foot.

During the same time as the US 84 study, data was obtained from three Long Term Pavement Performance (LTTP) Specific Pavement Studies (SPS) within Class 3 (SPS-3: Preventative Maintenance Effects of Flexible Pavements). Table 2.5 shows this data along with the data from Howard and Baumgardner (2009) using CRS-2 asphalt emulsion.

Table 2.5

Collection of Frosted Marble Test Data Using Benedict's Original Method

kg-cm	**Curing Condition**		
Location	**15 hr Air**	**4 hr oven + 2 hr air**	**15 hr oven + 2 hr air**
Midwest	10.5	17.0	21.5
Northeast	16.0	19.0	21.0
South	17.5	21.0	31.5
US Hwy 84	13.2	19.0	34.1

Howard et al (2009) compared Benedict's original *FMT* method to a modified method that was developed at PTSI. The original protocol is described with a sequential numbering, while corresponding steps of the modified protocol are shown with sequential numbering and the subscript (M).

1 Replace the standard 28.6 mm diameter cohesion tester foot with the 50 mm hooked foot and adjust to contact the frosted marbles slightly below the center of the marble. Lock in place with the jamb nut.

1_M No Modifications.

2 Adjust air pressure to 70 kPa to minimize friction. The equipment can be operated without the air pressure, but convenience is lost as a result.

2_M Current protocol is to adjust the air pressure to just enough to raise and lower the foot which reduces potential for testing errors such as the torque shaft not being vertical.

3 Add 9.0 $\pm$ 0.2 g of chip seal emulsion to each of the three, 1.55 $\pm$ 0.05 mm deep troughs of the plate. Place on a level sureface and allow the emulsion to seek a level position. Original test protocols did not specify the temperature of the tray when adding emulsion.

3_M Current protocol is to place heated emulsion into trays that have been heated to the same temperature. Heated Emulsion is placed into heated trays in ambient conditions.

4 When emulsion is level, an acrylic template is placed directly over the tray and 15 marbles are added. Original protocols interred that the tray sit for 5 minutes with emulsion prior to application of the marbles. The template may be removed in a few minutes or when the initial set occurs; it is mainly for alignment.

4_M As soon as a level position is obtained within the emulsion, the template is placed and frosted marbles are added. The tray is immediately taken into the environmental chamber with the template attached. Once in a stable position in the chamber the template was removed and the tray remains in the chamber for continuous curing throughout the test. The modified approach embeds the marbles quickly to allow wicking of the emulsion up the sides of the frosted marbles and to prevent skin formation within the emulsion.

5 Cure specimens: A) 15 hours at ambient conditions; B) 4 hours at 60 C in a forced draft oven followed by 2 hours cooling; and C) 15 hours at 60 C in a forced draft oven followed by 2 hours of cooling.

5_M The samples are cured in a very different fashion relative to the original work. The samples are not cooled prior to testing, rather they remain in the environmental chamber (54.4 to 57.2 C) during both curing and testing. The experimenter enters the chamber to test the samples. Heat lamps are used to provide the temperature, and a minimum of 75 mm distance is left between all curing samples. The samples are tested after the following number of hours of curing; 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 24, 48, and 120.

6 After each specified curing period the tray is positioned on the cohesion tester base with a hooked foot for a 2-point static contact. The tray is held firmly in place while the torque wrench is applied to the upper rod end and twisted in a quick and firm motion. The torque required to dislodge the marble from the emulsion is read and recorded as a data point. The average torque values of 5 successive data point in each trough for the curing period stated is recorded as one chip retention strength test point. All 3 rows per trough are tested in one interval.

6_M The average torque values of 15 successive data points in a trough for the curing period stated is recorded as one chip retention strength test point. All 3 rows are tested in one interval. Each row contains one emulsion. The motivation for increasing the number of data points per test was to reduce variability. The original testing was conducted in triplicate, the equivalent of one trough plate was required for triplicate tests, and three curing conditions were utilized. Of the 15 data points taken for each coordinate plotted using the modified method, the highest and lowest values were discarded alongside any others deemed erroneous due to engineering judgement. The plots in the modified method are more logical than the original method due to the curing approach and provide potential for more fundamental understanding of emulsion quality.

Howard et al. (2009) confirmed that the modified *FMT* produced promising attributes, but also has obstacles to overcome prior to widespread use. Curing is a major obstacle to overcome with the *FMT*. The only rational used for curing conditions was that pavement temperatures approaching this value are observed in Mississippi. King and King (2008) stated that emulsion should be completely broken and the cure time depends upon the emulsion, the existing pavement, and the climate. Curing of emulsions in the early stages (especially formation of films) can greatly affect the initial strength. Kucharek et al (2006) tested both cationic and anionic emulsions with and without polymer modification using methods including the *FMT*. The curing protocol consisted of samples in ambient conditions for 2, 4, 6, and 24 hours. Results showed that cationic emulsions to cure at a steeper rate relative to the other emulsions. Strength gain rate was fastest with use of CRS-2P emulsions. CRS-2P emulsions were more advantageous.

Howard et al. (2009) also concluded that the other major obstacle in the *FMT* is testing variability. The shaft not being vertical during the torsional process can cause problems. The marble hitting the tray can cause artificially high readings. Values in excess of 40 kg-cm are often considered suspect. The *FMT* appears valuable for evaluation of binder curing, assessment of film development during curing, and assessment of excessive stiffening during early service. The test was not necessarily recommended for other purposes. It should be combined with other tests for a system level evaluation for performance specifications.

2.7 Lessons Learned From Literature Review

Testing viscosity changes of emulsion application rates typical for chip seal treatments was not found in literature. An 85 % Toluene and 15 % Ethanol solvent blend appears applicable to extraction of near surface bituminous material consisting of the original aged binder and newly applied bituminous material. This solvent blend was reported to only soften bituminous materials under high oil bath temperature and low asphalt concentration and not to be as effective at removing absorbed asphalt (a positive for this study). Recovering asphalt is a critical process in which short recovery time, reduced temperature at early stages, and a use of a vacuum can reduce the effects of hardening on binder. Viscosity from aged pavements has shown that it decreases with depth. The *FMT* was found to have the potential in showing the effects of emulsion strength related to chip retention.

CHAPTER III

EXPERIMENTAL PROGRAM

3.1 Experimental Program Overview

A large portion of this research was to develop the experimental program. This thesis is part of a comprehensive study with a goal to develop performance based specification guidance for chip and scrub sealing activities for the *MDOT* in State Study 211. This thesis focuses on three areas: (1) rejuvenation effects of aged asphalt binders due to emulsion treatment; (2) emulsion adhesion strength and its relationship to chip retention; and (3) moisture loss of asphalt emulsions. In summary, over 1600 cores were obtained from aged in situ pavements (approximately 1000 cores were used in this thesis); more than 150 asphalt extractions and recoveries were performed; over 180 viscosity tests were conducted; and over 200 Frosted Marble Tests were performed.

3.2 Materials Tested

The materials used for this project were ten emulsions of seven different categories and two asphalt pavements. Three companies supplied the emulsions: Ergon Asphalt and Emulsions, Inc.; Blacklidge Emulsions, Inc.; and Road Science LLC (formerly SEM Materials); and these companies represent practically all Mississippi's suppliers as of the writing of this thesis. These emulsions represent materials delivered into the state of Mississippi for use in seal treatments.

3.2.1 Asphalt Emulsions

The seven emulsion categories tested were: CRS-2, CRS-2P (SBR), CRS-2P (SBS), PASS-CR, CHFRS-2P, Road Armor, and CFS-2HP. Table 3.1 shows the numbering system used in this thesis. As seen, multiple samples of emulsions CHFRS-2P, CRS-2P (SBR) and CRS-2 were incorporated and given different numbers since they did not necessarily have properties maintained between sampling intervals. The PASS-CR emulsion was the only emulsion that was a field sample; it was obtained from Highway 17 in Carroll County, Mississippi during State Study 202. For emulsions 1 and 2, multiple samples were taken with essentially the same properties and were thus given the same emulsion number.

PTSI, Road Science, and Blacklidge conducted property testing on all seven emulsion types that were used for this project. AASHTO M-208 was conducted on all products. The particle charge test was omitted while emulsion pH and particle size analysis were added. Distillation tests were conducted by the standard method (260 C) for the CRS-2 emulsion; while the six other polymer modified emulsion types were conducted by the modified method (177 C). The modified approach was conducted at the same bottom thermometer distillation temperature for modified emulsions. Table 3.2 shows the fundamental properties results for the emulsions that were used for the majority of testing with this experimental program. For emulsions 8, 9, and 10, properties were taken at the plant and are provided in Table 3.3. These emulsions were only used for select purposes as shown in Table 3.1.

Table 3.1

Emulsion Numbering System

Emulsion			Production		Testing Conducted[B]		
No	Type	Supplier[A]	Location	Date	Visc	FMT	wc_{LOSS}
1	CRS-2	1	Plant	10/2008	X	X	X
				05/2009		X	X
2	CRS-2P (SBR)	1	Plant	10/2008	X	X	X
				05/2009		X	X
3	PASS-CR	1	Plant	11/2007	X	X	X
4	CHFRS-2P	1	Plant	11/2008	X	X	X
5	CRS-2P (SBS)	2	Laboratory	05/2009	X	X	X
6	Road Armor	2	Plant	05/2009	X	X	X
7	CFS-2HP	3	Laboratory	05/2009	X	X	X
8	CHFRS-2P	1	Plant	08/2009		X	X
9	CRS-2	1	Plant	08/2009		X	X
10	CRS-2P (SBR)	1	Plant	08/2009		X	X

A: Ergon (Mt. Pleasanton, TX terminal)-1. Road Science (Garden City, GA terminal for plant; Tulsa, OK for laboratory)-2. Blacklidge (Gulfport, MS)-3.

B: Visc – viscosity testing (Section 3.5), FMT – Frosted Marble Test (Section 3.6), wc_{LOSS} – moisture loss testing (Section 3.7)

Table 3.2

Fundamental Properties of Emulsions Used for Majority of Testing

Emulsion No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Sieve (%)	0.01	0.04	0.01	0.02	0.00	0.05	0.01
50 C SFS Visc. (s)	452	73	94	59	124	145	36
pH	3.68	3.91	2.66	2.62	1.78	2.26	3.00
Particle Size (µm)	4.01	7.29	5.29	7.12	2.58	5.48	4.51
Demulsibility (%)	94	80	61	81	59	101	67
24 Hr Storage (%)	0.10	0.14	1.05	2.50	-0.20	0.02	0.04
Residue (%)	69.9	68.1	67.6	69.8	68.5	70.7	72.3
Oil by Vol. (%)	0.125	0.125	0.625	0.250	0.100	0.500	0.500
25 C Pen (dmm)	130	104	250	129	122	84	68
25 C Duct. (cm)	116.5	50.0	58.3	150.0	145.0	114.0	80.0

Table 3.3

Fundamental Properties of Emulsion Used for Selected Testing

Emulsion	**8**	**9**	**10**
122 C SFS Visc. (s)	240	240	215
Demulsibility (%)	79	84	83
Oil by Vol. (%)	0.250	0.125	0.125
Residue Test 1	68.7	67.6	67.9
Residue Test 2	68.9	66.9	68.4
Residue Test 3	69.1	67.4	68.0
Residue Avg	**68.9**	**67.3**	**68.1**

1: AASHTO T 59-09 performed by author upon arrival.

Emulsions are not designed to be a shelved product, thus certain steps are to be taken to ensure the properties at the construction site are achieved for laboratory testing. Typically, an emulsion is delivered in bulk shipments that have been properly agitated and not allowed to cool to ambient conditions. All emulsions that were used were stored in either 1.9 or 3.8 liter containers. These containers were stored in ambient conditions until use.

Handling emulsions properly was essential in order to produce large numbers of acceptable samples. Improper handling will result in the emulsion breaking prematurely or cause other problems that will lead to faulty test data. Each supplier gave instructions for splitting, stirring, and reheating the emulsion. Two re-heat procedures were used depending on emulsion type: oven and water bath methods.

Several emulsions arrived in 19 liter containers and were distributed into 1.9 to 3.8 liter containers. The emulsion and container were placed in a 60 C oven for a period of 12 to 18 hours, stirred mechanically for a period of two minutes, then poured from the 19 liter container into a heated 1.9 or 3.8 liter container.

The number of re-heat cycles for the emulsion was minimized. The material was heated in the original container, re-mixed, and separated into smaller containers for use in laboratory testing.

After the baseline property testing, the emulsions were stirred approximately once per month. They were heated to 60 C and stirred to place the particles back into suspension. During stirring, if the operator noticed any settlement in the bottom of the container that was soft (pudding consistency or thinner), the material typically went back into suspension with no adverse affects; whereas hard settlement (peanut butter consistency or thicker) typically did not go back into suspension and the material was discarded. ASTM D 6933, sieve test, was also performed on each container of emulsion using a Number 20 sieve. Approximately 100 grams of emulsion was poured through the sieve and the container of emulsion was discarded when 1 gram of the 100 gram sample was retained on the sieve.

Emulsion from suppliers 1 and 3 were heated for use using the oven method. A desired amount of emulsion was placed in a 60 C oven for a period of at least 4 hours. After the emulsion was heated, the emulsion was slowly rolled end-over-end to provide consistency of the product. Failure to do so would have resulted in a watery mixture leaving most, if not all, emulsified particles at the bottom of the container. The lid of the container was taken off and a thermometer placed in the container to measure the temperature of the emulsion. Once the emulsion reached 60 C, it was ready to be applied to cores or used for other testing.

The water bath method was used for emulsions from supplier 2. A 3.8 liter container of emulsion was placed in a 60 C water bath. A 6.3 mm spacer was placed in the bottom of the bath to prevent overheating the bottom of the container of emulsion, and water was placed in the bath to cover ¾ of the container containing the emulsion. The emulsion was slowly stirred with a stirring rod and temperature was measured. Once emulsion reached temperature, the emulsion was ready for use.

3.2.2 Asphalt Concrete Pavement

Two in-situ pavements were used for this project: (1) frontage road adjacent to Highway 25 in Starkville, MS *(FR),* and (2) abandoned portion of Highway 45 in Crawford, MS *(Hwy 45)*. The rationale for using these pavements were: (a) the two pavements had different permeabilities; and (b) the pavements were not in service but had been in the past; (c) the condition of the pavements differed; and (d) the categories of the pavements were different. The pavement densities were found for analysis purposes for *FR* and *Hwy 45* and are 2098 kg/m^3 and 2146 kg/m^3, respectively.

3.2.2.1 Obtaining Asphalt Concrete Slabs

Pavement that was free of large cracks, pot holes, and other major distresses was considered useable. The pavements were marked with spray paint or pavement chalk in a grid pattern in which each portion of the grid was approximately 76 cm square. A gas powered walk behind wet saw was used to cut the grid into blocks. Ten to twelve 190 liter barrels of water were used to complete the sawing of a pavement which involved many cuts. The first cut was 12.5 mm to 19 mm deep. Subsequent cuts were made in increments of 12.5 mm to 19 mm until reaching depths of 50 mm for *Hwy 45* and 150 mm for *FR* for safely retrieving the slabs.

Figure 3.1 shows the procedure for cutting the pavements. Part (a), shows *Hwy 45* pavement being observed for determining an adequate grid location. Part (b) shows the marking of a grid on the pavement. Part (c) shows the saw cutting the grid into the pavement. Part (d) shows the backhoe retrieving the slabs in which the operator of the backhoe positioned the slabs into a trailer. Cardboard was placed in between the slabs for protection of the surface. This removal of slabs left a large gap in the existing pavement; *MDOT* personnel patched the sections. The slabs were brought to campus and stored outside prior to coring.

(a) Observing Pavement for distresses

(b) Marking of Grid

(c) Sawing of Grid

(d) Retrieving Slabs

Figure 3.1 Obtaining Asphalt Pavement

3.2.2.2 Coring Asphalt Concrete Slabs

Asphalt slabs were gathered from a local demolition project and used to develop handling, coring, marking, and cutting (Section 3.3.2) procedures for the slabs prior to before coring the actual pavements. The specimens produced using these procedures were 150 mm diameter cores that were 38 mm to 50 mm thick. Once these procedures were developed, the pavement from the demolition project was disposed.

Before coring began on a slab from the test pavements, the slab was carefully inspected and marked with pavement chalk for cracks, irregularities, and any other deficiencies as they were not permitted in the cores. The slab was then moved by pry bars, pallet jack, flat dolley, or combinations of these to the coring area. The slab was leveled using newspaper, plywood wedges, pieces of asphalt, or combinatations of these prior to coring. Approximately 15 cores could be produced from each slab. Concrete blocks were placed around the edges of the slab to prevent rotation. Coring started at one of the four corners of the slab. Four cores were produced on each side of a slab. After four cores were produced, the slab was either (a) rotated 90˚ or (b) excess was broken off using a mallet and coring of slabs resumed. Coring time, including set up and clean up took on the order of 15 minutes per core in absence of difficulties. After a core had been cut, it was retrieved from the slab, washed free of debris, and placed under a fan to dry. This drying period lasted several days, after which the core was ready for use. All equipment used in the coring of asphalt specimens was serviced every 250 cores which included inspection for wear, greasing, and overall cleaning.

Cores were stored in a cool dry place. Cores were given a random number and were marked 6.3 mm from the top using a 6.3 mm thick, 150 mm diameter PVC pipe.

On the bottom of every core, a number was given to indentify pavement type, future emulsion type, and future application rate. Then the core was considered suitable for testing.

3.2.2.3 Permeability of Asphalt Concrete

Permeability tests were performed on cores with no emulsion applied to them. Three cores were randomly obtained from each pavement and permeability tests were performed on each core using ASTM PS 129-01. This test was administered multiple times for each core. This first test was to flush any loose debris inside the core, then three replicates were used in calculating the permeability of each core. The reported permeability value was the average permeability from each of the three cores from each pavement. In the test specifications, time is terminated when a sample passed thirty minutes, however, time continued being recorded after thirty minutes of testing in this research. Equation 3.1 was used for determining the permeability of samples.

$$k = \frac{al}{At}\ln\left(\frac{L_2}{L_1}\right) \tag{3-1}$$

where:

k	= Permeability of asphalt (cm/sec)
a	= Inside cross sectional area of standpipe (cm^2)
l	= Thickness of test specimen (cm)
A	= Cross sectional area of specimen (cm^2)
t	= Time (seconds)
L_2	= Hydraulic head of specimen at Upper time (cm)
L_1	= Hydraulic head of specimen at Lower time (cm)

3.3 Preparation of Near Surface Treated Test Specimens

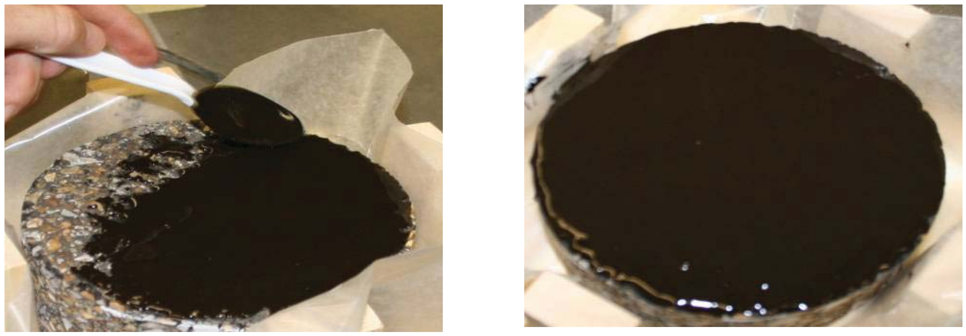
Near surface treatment specimens consisted of applying an emulsion to a core. Four application rates were used for each emulsion to apply to cores: 0.00, 0.81, 1.36, and 1.81 L/m^2 (0.00, 0.20, 0.30, and 0.40 gal/yd^2).

3.3.1 Application of Emulsion to Cores

A reheated small container of emulsion was poured into a pre-heated 3.8 liter paint can with a cover and was kept on a hot plate or in a water bath to maintain the temperature of 60 C. This container remained covered except when material was being removed for application. A random core was placed onto the scale with tin foil or wax paper and was tared. The correct amount of emulsion was applied to the surface of the core using plastic spoons and knives used to take emulsion from the heated container and spread it uniformly onto the core. To simulate the shot rate of interest, the desired shot rate ($\boldsymbol{X}$ L/m^2) was multiplied by 18.6 to determine the amount of emulsion in grams to apply to a core. The amount of emulsion for each core with the appropriate application rate was as follows and should be taken as $\pm$ 0.05 L/m^2 ($\pm$ 0.01 gsy): *(Note: Slight amounts of emulsion was added or subtracted to account for behaviors observed during preliminary testing).*

- 0.91 L/m^2 apply 17.5 $\pm$ 0.1g
- 1.36 L/m^2 apply 25.5 $\pm$ 0.1 g
- 1.81 L/m^2 apply 33.4 $\pm$ 0.1 g

Figure 3.2 (a) shows the application of emulsion to a core using plastic spoons, while part (b) shows a finished core. Once emulsions were heated and applied to cores, the remaining emulsion was discarded. Figure 3.3 shows a group of treated cores after the emulsion had been applied to them.



(a) Emulsion Application to core (b) Finish core after treatment

Figure 3.2 Emulsion Application to Near Surface Treatment Specimens

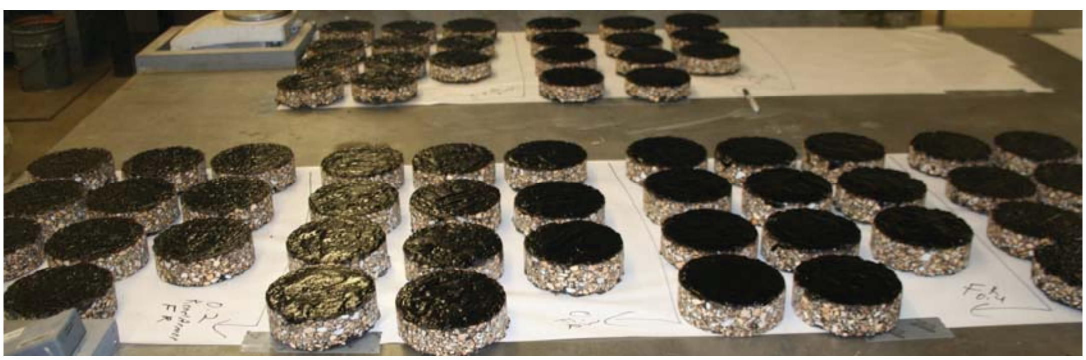
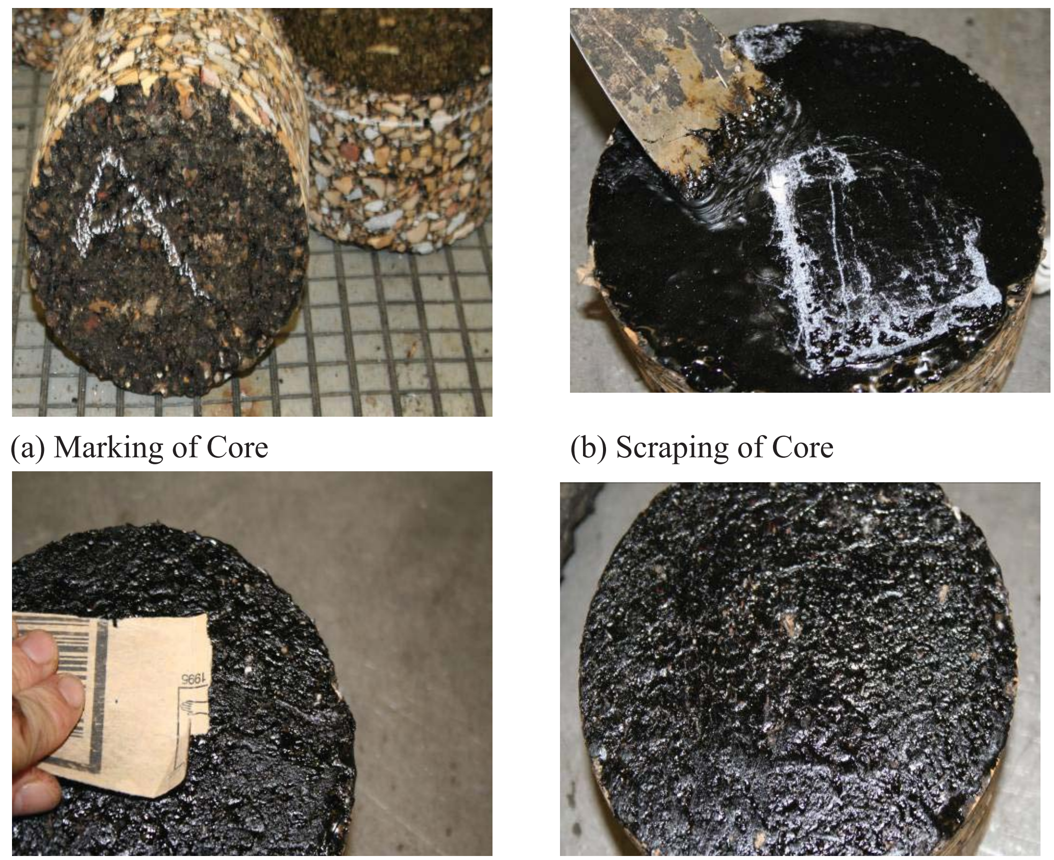


Figure 3.3 Near Surface Treatment Specimens Post Emulsion Application

Fifteen to twenty days were allowed for the cores to cure after emulsion treatment in ambient laboratory conditions that were free of dust or other disturbances. Cores were left undisturbed for a minimum of 96 hours after application (Figure 3.3), and thereafter, the cores were stored on shelving until a constant mass was obtained (verified by monitoring mass loss with time). After obtaining a constant mass, the cores sat for a minimum of 96 additional hours to allow complete solvency and/or volatile loss to occur. Thereafter the cores were considered ready for testing.

All specimens that were tested were either scraped (*SCR*) or unscraped (*NS*). Unscraped specimens were unaltered relative to the end of curing described in the previous paragraph. Figure 3.4 shows the scraping procedure that was developed for the cores. Part (a) shows a core being marked while parts (b) and (c) show a core being scraped and sanded. Part (d) shows the finished product of the scraping procedure. Emulsions 1 to 7 were tested in a scraped condition and emulsions 1 to 4 were also tested in the unscraped condition. After curing, cores to be scraped were heated at 60˚ C for approximately one hour. After heating, cores were taken out of the oven, weighed, and the emulsion was then scraped off the cores using a 25 mm scraper (putty knife). A piece of P 60 grade sandpaper was then used to remove any excess emulsion. The core was considered fully scraped when at least ten aggregates were visible through the emulsion. The amount of emulsion scraped from a core was recorded.



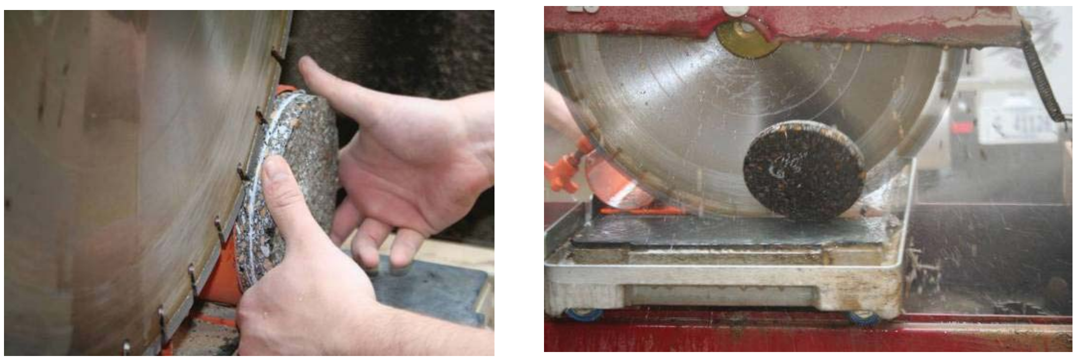
(a) Marking of Core
(b) Scraping of Core
(c) Sanding of Core
(d) Finished Scraped Core

Figure 3.4 Scraping Procedure of Emulsion Applied Core

3.3.2 Removal of Near Surface Test Specimens

Figure 3.5 shows the slicing procedure that was developed for this thesis. Part (a) shows a pre-marked core being aligned in the clamp prior to slicing, and part (b) shows a core having the top 6.3 mm sliced *(Note: 9.5 mm and 12.5 mm thickness were also sliced and evaluated during parts of the experimental program in the same manner)*. After the core was sliced, the cut portion of the core was placed into a tray and the remaining portion was disposed. The slicing process for the cutting procedure took on the order of 10 minutes per slice barring difficulties.

An MK Diamond Chop Saw was used for the aforementioned slicing procedure. Preliminary work was performed to determine the minimum core thickness that would allow a 6.3 mm slice to be removed evenly from the surface. It was determined that a core with a minimum thickness of 38 mm was suitable as it allowed adequate room for clamping.



(a) Aligning core in clamp (b) Core being sliced

Figure 3.5 Slicing of Cores

The surface slices were placed under a fan to dry the excess water for 2 to 4 hours. Multiple slices were needed for a single test, so they were combined at this stage. The composite sample was labeled with emulsion type, application rate, scraping protocol, and pavement type. Thereafter it was placed into an 60 C oven for approximately one hour to slightly soften the binder prior to placement on a hard surface where it was broken up with an 11 kg hammer into small pieces (maximum size of peices being 19 mm) to allow asphalt extraction to be more efficient. *Note: Aggregates were not of interest, so breaking particles was of no concern.*

3.4 Extraction and Recovery Test Procedures

The broken up composite sample of a given emulsion type, application rate, scraping protocol, and pavement type had its bituminous material extracted and recovered according to AASHTO T-319-08. Two replicates of each combination of emulsion type, application rate, scraping protocol, and pavement type were evaluated using these procedures while three replicates were made on control specimens.

Several issues arose for these tests which are: solvent selection, soak time, and the number of washes needed to extract the non absorbed asphalt in a sample. The solvent mixture used for this project was an 85 % Toluene and 15 % Ethanol mixture by volume. An 85 % Toluene and 15 % ethanol mixture was used instead of a TCE or TCE/ethanol mixtures since: (1) the selected solvents tend to be less aggressive than solvents such as TCE; and (2) easier to extract only the non absorbed asphalt in an asphalt mixture. Section 2.4 discussion was also significant in choosing this solvent mixture. Two 45 $\pm$ 5 minute soakings were used to allow the solvent to extract the binder from the mixture.

3.4.1 Binder Extraction Test Procedure

The difference in this test and the standard method was that a filter was placed on the bowl to prevent the finer aggregates from intruding into the solvent/asphalt mixture. Figure 3.6 shows the extraction test being conducted. Part (a) shows the set up for the extraction test. Part (b) shows the asphalt and solvent mixture flowing out of the sample. A centrifuge cup (Part (c)) with a lip on the open end of the cup was placed inside the high rate centrifuge (Part (d)). This lip provided a barrier preventing fines (minus No.

200 sieve) to enter the solvent-asphalt mixture. This test usually took about two hours to complete.

(a) Set up of Extraction Device

(b) Flowing Solvent & Asphalt

(c) Placing Cup into High-Rate Centrifuge

(d) Set up of Centrifuge

Figure 3.6 Extraction Test Procedure

Preliminary extraction testing was performed to determine the number of washes each pavement needed in order to extract only the effective binder from a sample (i.e. no absorbed binder). Both pavements with no emulsion were used for this set of experiments. For each pavement, 1, 2 and 8 washes were used. Eight washes (for *FR*) and seven washes (for *Hwy 45*) completely removed all binder for a 1,000 gram sample, thereafter 1 and 2 wash tests were performed. Figure 3.7 shows the asphalt content results from both pavements. It was assumed that on the order of 1.0 % of the total asphalt was absorbed. The results show that two washes extracts, 5.3% for *FR* and 5.7% for *Hwy 45*, which are the 88.0% and 85.0% of the total asphalt respectively. Figure 3.8 shows the aggregates after a given number of washes.

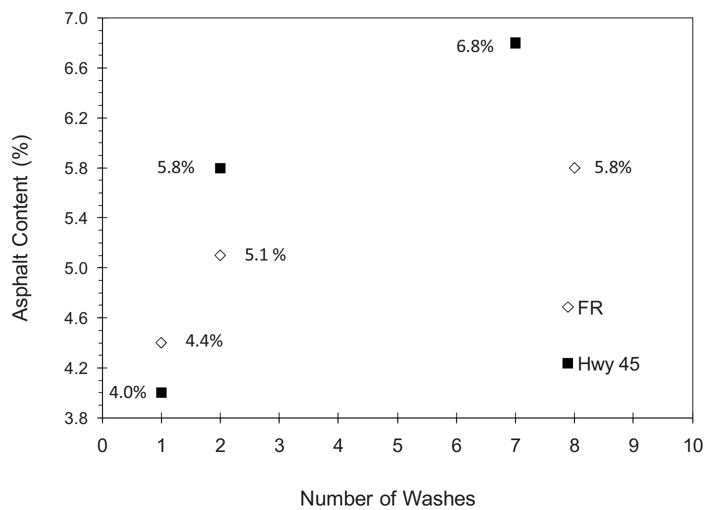
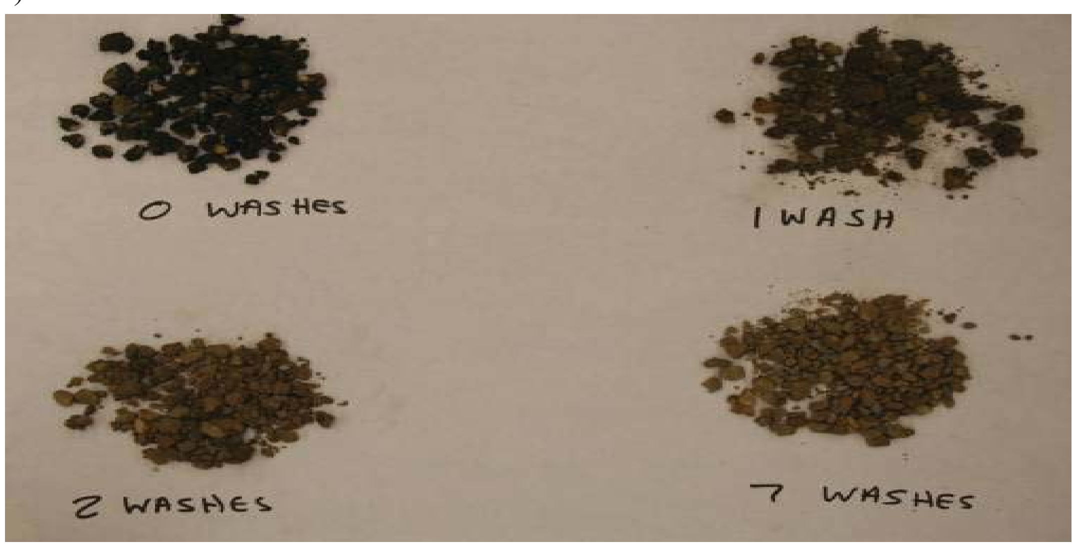


Figure 3.7 Extraction Wash Test

(a) *FR* Wash Test



(b) *Hwy 45* Wash Test

Figure 3.8 Wash Test for Pavements

3.4.2 Binder Recovery Test Procedure

The recovery equipment used was a rotational-vaporation (Roto-Vap). Once the binder and solvent mixture had been fully extracted, it was placed into the recovery apparatus through the tube at the top of the apparatus denoted as number 1 in Figure 3.9.

The bulb was heated to 140 C by the fluid bath (number 2) before the binder/solvent mixture was added into the apparatus.

Figure 3.9 Recovery Apparatus Set-up

After 500 mL of solvent had been evaporated, the temperature and vacuum was slowly increased to 180 C and 650-700 mm of Hg respectively. When the solvent dropped less than one drop per 30 seconds, an additional 30 minutes at these conditions ensured that the solvent had evaporated out of the binder. Recovered binder was poured into a tin and placed into a 165 C oven for an additional 10 minutes to ensure that all the solvent had left the binder. After ten minutes, the tin was removed from the oven, and 9.5 to 10 grams of recovered binder was poured into the viscosity cups. The amount of binder obtained per recovery was enough to fill four viscosity cups. Bioact and acetone were solvents used to clean equipment and tools. Acetone was placed onto the bulb to prevent oil splattering prior to testing. The heat from the oil bath evaporated this chemical prior to adding the solvent/asphalt mixture to the recovery apparatus.

A mixture of ice and water was used to aid the condensing process of the solvent, (denoted as a number 3 in Figure 3.9) to prevent overheating. One bag of ice and 2 L of tap water was placed into a 19 L bucket. A pump was submerged into the mixture to pump cold water into the apparatus during testing.

3.5 Viscosity Test Procedure

Viscosity testing followed the standards set by AASHTO T 316-04 which measures the dynamic viscosity in a rotational manner. In April, 2008, the Brookfield Viscometer was calibrated using a N450000 calibration fluid. Results showed that the viscometer was within specifications for both AASTHO and ASTM recommendations of $\pm$ 2% and $\pm$ 1% respectively for the higher temperature, and was within the Brookfield recommendations of + 0.9% at the higher temperature. Table 3.4 shows the results from the calibration of this viscometer. All samples were evaluated at 135 C and 165 C using a S27 spindle. For a given sample, one replicate was made for each temperature. During testing, there were three readings at each temperature.

Table 3.4

Calibration of the Brookfield Viscometer

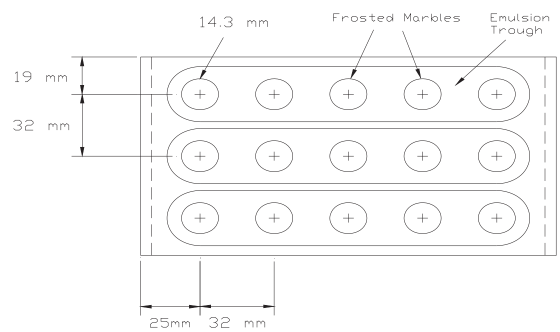
Temperature ˚C	Calibration Value (cP)	Average Value (cP)	% in Compliance
65	107100	106000	-1.0
135	2606	2629	+0.9

3.6 Frosted Marble Test Procedure

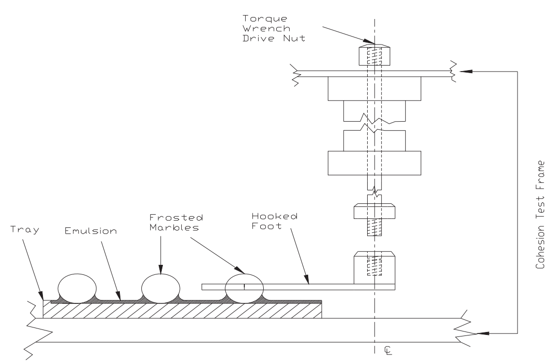
There are no ASTM or AASHTO specifications that reference the *FMT* testing protocol. C.R. Benedict developed the *FMT* using a variety of curing conditions (see Section 2.6). PTSI modified Benedict's *FMT* method for curing and testing of specimens in an attempt to reduce variability and improve the curing protocol. For this thesis, an additional modification was also used along the PTSI method for using the *FMT*. The testing that was adopted for this research was a third iteration of the *FMT* to improve Benedict's and PTSI methods.

For this thesis, the *FMT* was implemented to capture the effect of moisture loss versus torque (*See Section 3.7 for information on moisture loss*). Tests were conducted in May and August of 2009. For the tests performed in May, emulsions 1 through 7 were used only once for the *FMT*. Three emulsions (numbers 8, 9, and 10) were used during the month of August 2009 and three replicates of the *FMT* test suite were performed for each emulsion.

Emulsions used for the *FMT* were handled and heated in accordance with *Section 3.2.1*. *FMT* test trays have three troughs machined into each tray, (Figure 3.10 (a)). Emulsion and trays were heated to 60 C, a tray was taken out of the oven, labeled with emulsion type, conditioning time, and weighed. Emulsion was then placed into a styrofoam cup, and a 10 mL syringe was used to transfer the emulsion from the cup into the tray. According to the specifications made by PTSI, 9.0 to 9.5 grams of emulsion was poured into each trough of the tray (27.0 to 28.5 g of emulsion total). After all troughs were filled, a template was placed on top of the tray, and the frosted marbles were applied to the emulsion. The tray, template, and marbles were taken to a 57 C environmental chamber where the samples were cured with minimal disturbances. Figure 3.11 shows the process of developing an *FMT* specimen. *(Note: The template was taken off of each tray after placement in the environmental chamber. Samples were positioned so that there was no direct heat from the lamps. This was to prevent premature setting of the emulsions.)*

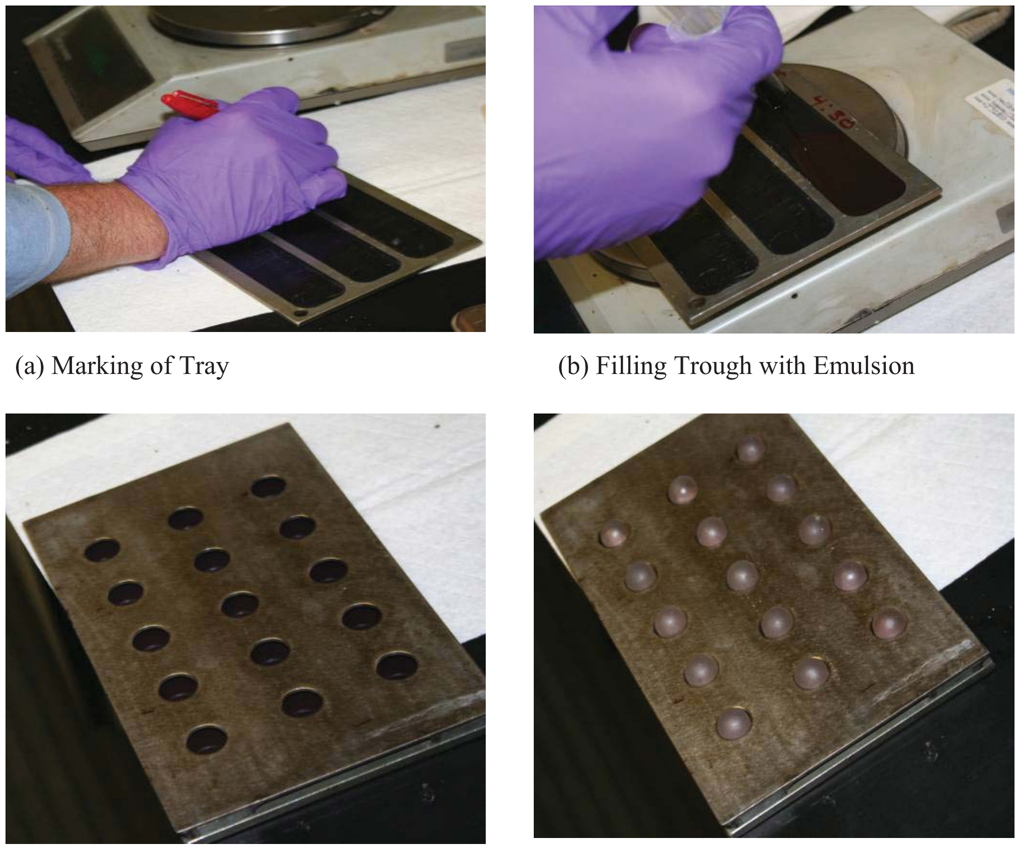


(a) Frosted Marble Tray Layout



(b) Testing Apparatus of Frosted Marble Test

Figure 3.10 Apparatus for the Frosted Marble Test (Howard et al. 2009)



(a) Marking of Tray (b) Filling Trough with Emulsion

(c) Placing template over tray (d) Placement of Marbles

Figure 3.11 Development of the Frosted Marble Specimen

An environmental chamber measuring 4 m by 2 m was modified by using heat lamps to meet the desired temperature. Samples were placed in this chamber for time periods of 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 24, 48, and 120 hours. *(Note: There was a sample tested at each of time period shown).* The sample remained in the same location until testing.

A cohesionmeter was used to test the specimens. For a specimen being tested, the air supply for the cohesionmeter was turned on 345 kpa. The specimen was then placed onto the device and a foot was lowered to the tray and positioned on each marble. This foot was rotated by the use of a torque wrench to measure the shear strength of the sample. The readings taken from the torque wrench were measured to the nearest multiple of 3 kg-cm.

Figure 3.12 shows the testing of the frosted marble specimens. The torque wrench used for this test is shown by a number 1 in the figure. The cohesionmeter is shown by the number 2 and the foot that is used to shear the marble is shown by a number 3. The *FMT* tray is shown by a number 4. The readings for each test were evaluated by either (a) eliminating the highest and lowest readings; or (b) eliminating the two highest and two lowest readings; or (c) using engineering judgement.

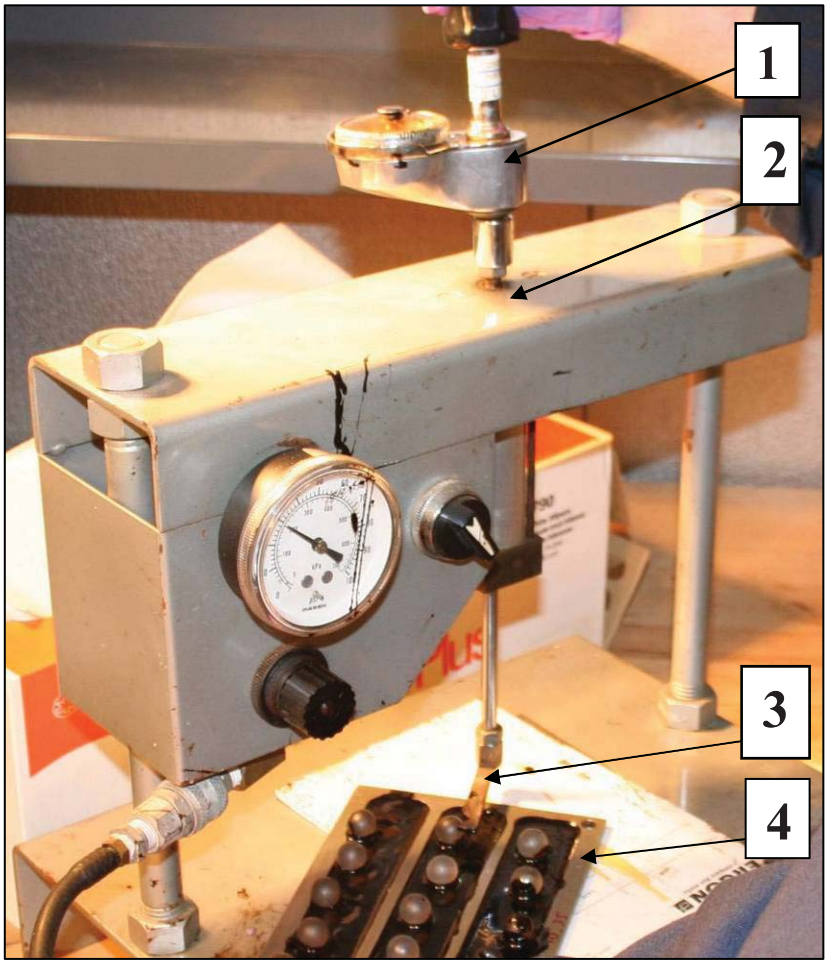


Figure 3.12 Testing of Frosted Marble Specimens

3.7 Moisture Content of Emulsions

Experiments were undertaken to determine moisture loss within asphalt emulsions. The primary motivation was for use in conjunction with *FMT* test data with a secondary purpose of obtaining emulsion for baseline viscosity testing. Three approaches were taken as seen in the following paragraphs. Tables 3.2 and 3.3 show the residue values that were used during calculations.

3.7.1 Moisture Loss Testing Using FMT Test Trays

The first phase was conducted on emulsions 1 through 7 during May of 2009 and the second phase was conducted during August of 2009 on emulsions 8, 9, and 10. The first phase in May 2009 was preliminary and the results unproductive in the sense of developing reasonable data. For the May 2009 testing, a tray with only emulsion was weighed prior to placement in the environmental chamber and then was taken to a scale where it was weighed after the frosted marble test at the appropriate conditioning time. *Note: The same specimen was repeatedly weighted to evaluate moisture loss.*

For the second phase of testing (August 2009), there were no frosted marbles applied in the troughs of the trays. For this testing emulsion residue was determined using the evaporation method of AASTHO T 59-09 at the same time as the *FMT* test was conducted whereas in May of 2009 a value obtained some time ago was used (the emulsions could have changed during this period). Equation 3-2 shows the calculation of an emulsion residue and Equation 3-3 shows the equation for moisture loss of an emulsion.

$$R = 1 - (B-CC)/(B-AA)) \tag{3-2}$$

Where,

R = Residue Expressed as a Decimal

AA = Weight of Container, Rod, and Tin Foil (grams)

B = Initial Weight (before heating) (grams)

CC = Final Weight (after heating) (grams)

$$wc_{loss} = \left(\frac{C}{(C + D) * U} \right) * 100 \tag{3-3}$$

Where,

wc_{loss} = Moisture Loss of Emulsion

C = Amount of Water Lost at Time Period (grams)

D = Amount of Solids at Time Period (grams)

U = $1 - R$

3.7.2 Moisture Loss Testing Using PVC Rings

In June of 2009 emulsions 1 through 7 were used in conjunction with PVC rings to evaluate moisture loss and to obtain material for rotational viscosity testing on the fully cured emulsion. In order to perform the tests, the author developed an apparatus to hold an emulsion at a 150 mm diameter spread.

This apparatus contained three parts; a piece of cardboard, a piece of wax paper, and a 150 mm diameter PVC pipe. Pieces of cardboard and wax paper were cut into rectangular pieces and sized so that the 150 mm diameter ring could be easily placed on the cardboard. Figure 3.13 shows moisture loss samples in the PVC rings.

Figure 3.13 Moisture Loss Testing Using PVC Rings

The samples were cured in ambient conditions until constant mass was achieved. Periodic readings were taken to evaluate moisture loss. Once the samples achieved constant mass, the samples were given 24 additional hours to cure and thereafter the sample was tested for viscosity. Equation 3-4 shows the equation for calculating moisture loss with this method.

$$wc_{loss} = \left(\frac{F}{(F+G)*H} \right) *100 \tag{3-4}$$

Where,

wc_{loss} = Moisture Loss of Emulsion

F = Weight of Water Loss (grams)

G = 25.5 – C Weight of Solids (grams)

H = 1 – Residue Value

3.7.3 Moisture Loss Testing Using Moisture Tins

Approximately 25.4 grams of emulsions 1 through 7 were poured into moisture tins and weighed to the nearest 0.001 grams. Two replicates of each emulsion were tested for moisture loss and for viscosity tests on the fully cured emulsion. Samples were taken from their curing conditions (Curing conditions were in a 60 C oven) and weighed at periodic time intervals. After testing for moisture loss, viscosity tests were conducted using the methods in Section 3.5.

CHAPTER IV

RESULTS

4.1 Introduction

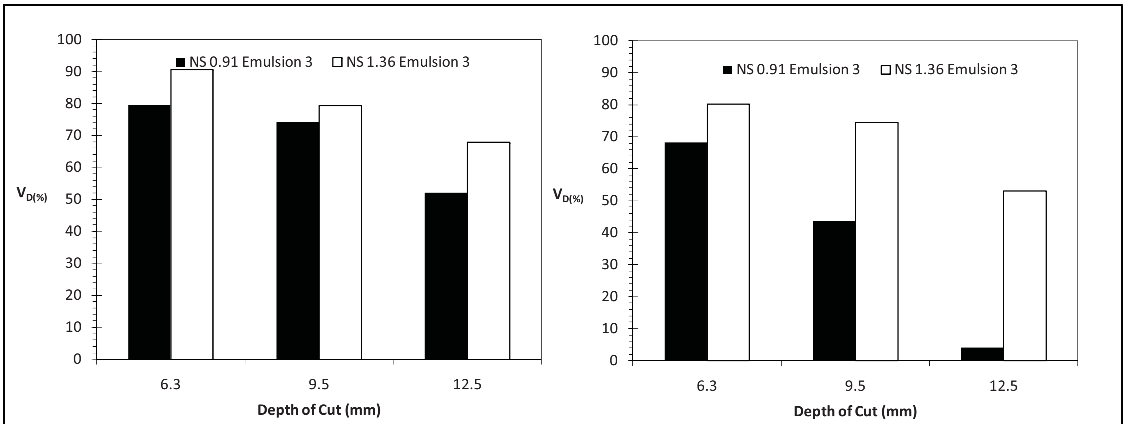
There were two main components analyzed for this thesis: (1) Viscosity testing of the near surface material from cores (mostly 6.3 mm thick slices) and (2) *FMT* testing of emulsions. Raw data from testing can be found in Appendix A (Viscosity Data), Appendix B (Extraction Data), Appendix C (*FMT* Data), Appendix D (Emulsion Moisture Loss Data), and Appendix E (Permeability Data). The percent decrease in viscosity ($V_{D(\%)}$) for each application rate at each thickness was determined using equation 2.2 for all analysis.

4.2 Viscosity Analysis

In the viscosity analysis, depths of 6.3 mm, 9.5 mm, and 12.5 mm were first tested for decrease in viscosity with emulsion 3. Based on the results of this test, four viscosity subcomponents were established: (1) The effect of emulsion type and scraping on percent decrease in viscosity; (2) The comparison of measured viscosity versus calculated viscosity; (3) The effect of application rate using the paired *t-test*; and (4) The comparison of effective asphalt content versus percent decrease in viscosity. These four subcomponents incorporated emulsions 1 to 7. Results from coring of Highway 17 (*Hwy* 17) were also provided (see *MDOT* SS 202 for details on the test section).

4.2.1 Percent Decrease in Viscosity in 6.3, 9.5, 12.5 mm Specimens

Eleven unscraped cores were used for each thicknesses at the 0.91 and 1.36 L/m^2 application rates. Figure 4.1 shows the results from this test.



(a) $V_{D(\%)}$ at 135 C (b) $V_{D(\%)}$ at 165 C

Figure 4.1 Percent Decrease in Viscosity for Emulsion 3 (*FR*)

Based upon the results of this test, it is shown that the $V_{D(\%)}$ steadily decreases with depth at both temperatures. This is likely due to aging/microcracking occurring more in the surface layer than in deeper layers of the pavement (an expected behavior). Based upon the results in this figure, the analysis concentrated on $V_{D(\%)}$ in the top 6.3 mm of the pavement. The thinner sections (top 6.3 mm) was chosen to consider the more critical depth of rejuvenation and since the smallest variability between test temperatures was observed in Figure 4.1.

4.2.2 Percent Decrease in Viscosity

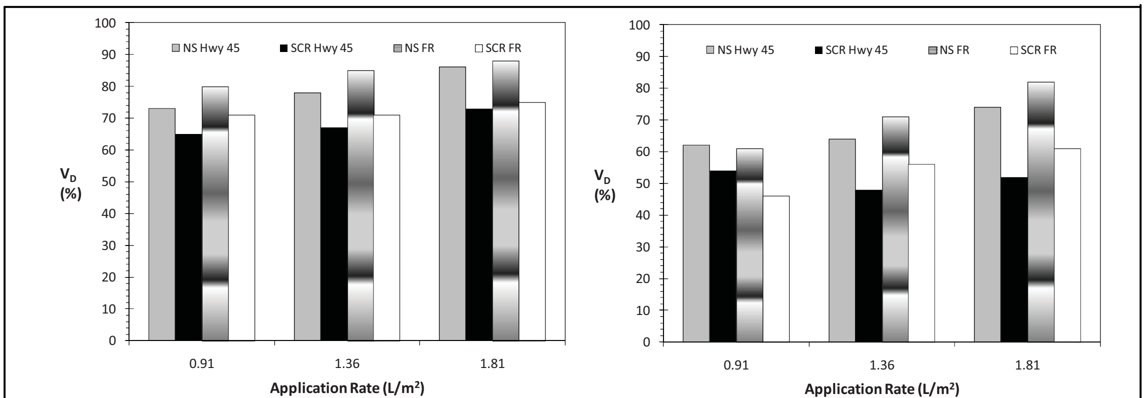
There were 72 data points for both *Hwy 45* and *FR* used in this analysis in which the top 6.3 mm slices were used. The untreated viscosity term (V_U) was the average value for all viscosity tests performed on the control (i.e. *FR* for 6.3 mm is 10550 cP at

135 C and 1494 cP at 165 C and *Hwy 45* for 6.3 mm is 9216 cP at 135 C and 1318 cP at 165 C). Figures 4.2 to 4.8 show the $V_{D(\%)}$ found for each application rate on each pavement using emulsion 1 to 7. Taking *Hwy* 45 values as an example, $V_{D(\%)}$ was calculated as follows for $V_{D(\%)}$ in first column of Figure 4.2 (a). *Note: Value used in* V_T *was from emulsion 1 using unscraped data at 135 C (Table A-2).*

$$V_{D\%} = \frac{V_U - V_T}{V_U}(100)$$

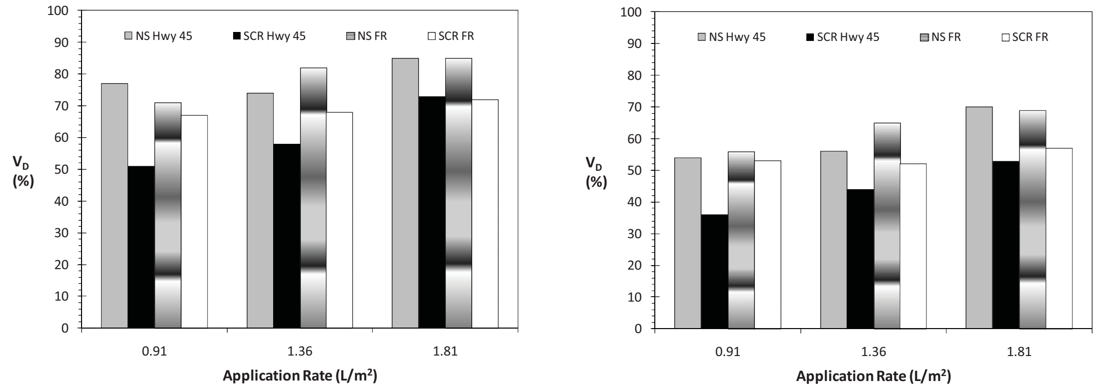
$$V_{D(\%)} = \frac{9216 - 2479}{9216}(100)$$

$$V_{D(\%)} = 73.1\%$$



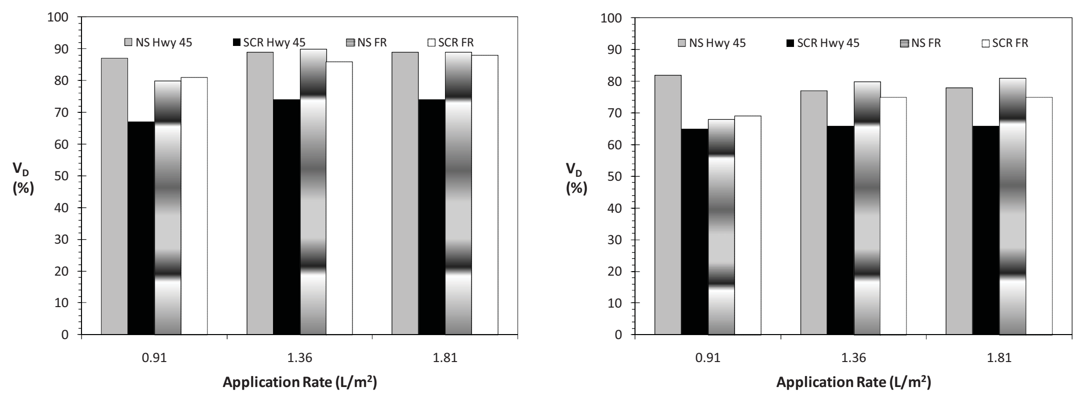
(a) 135 C (b) 165 C

Figure 4.2 Percent Decrease in Viscosity for Emulsion 1



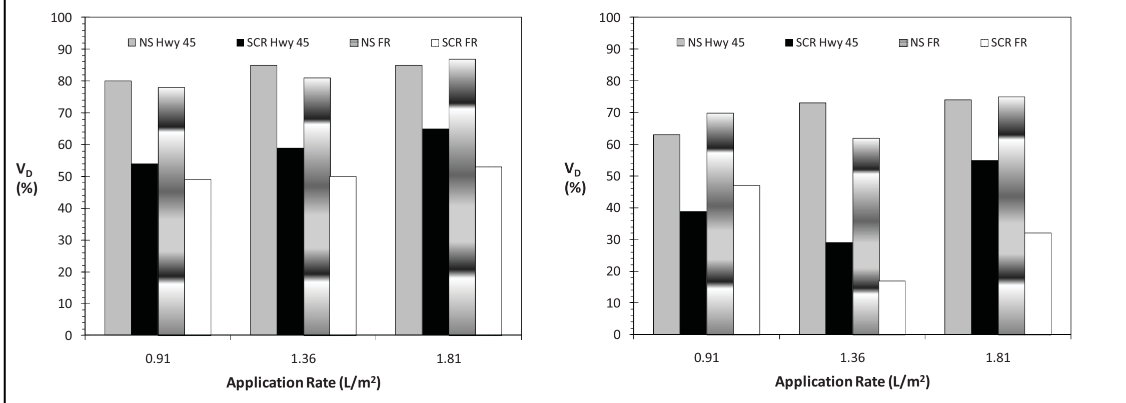
(a) 135 C (b) $V_{D(\%)}$ at 165 C

Figure 4.3 Percent Decrease in Viscosity for Emulsion 2



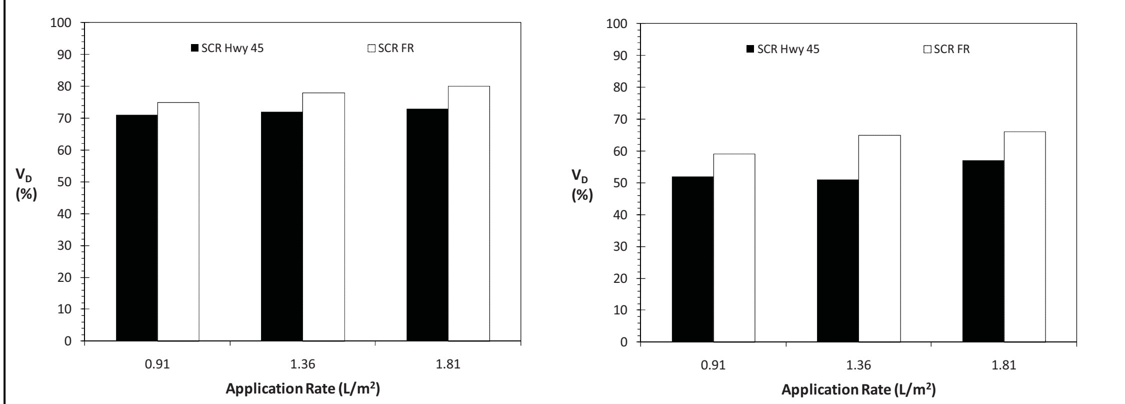
(a) 135 C (b) 165 C

Figure 4.4 Percent Decrease in Viscosity for Emulsion 3



(a) 135 C (b) 165 C

Figure 4.5 Percent Decrease in Viscosity for Emulsion 4



(a) 135 C (b) 165 C

Figure 4.6 Percent Decrease in Viscosity for Emulsion 5

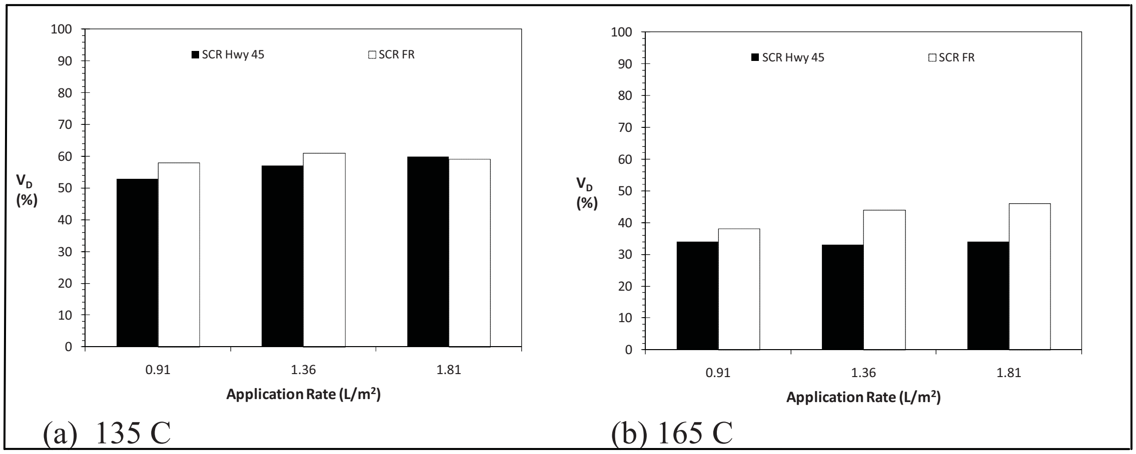


Figure 4.7 Percent Decrease in Viscosity for Emulsion 6

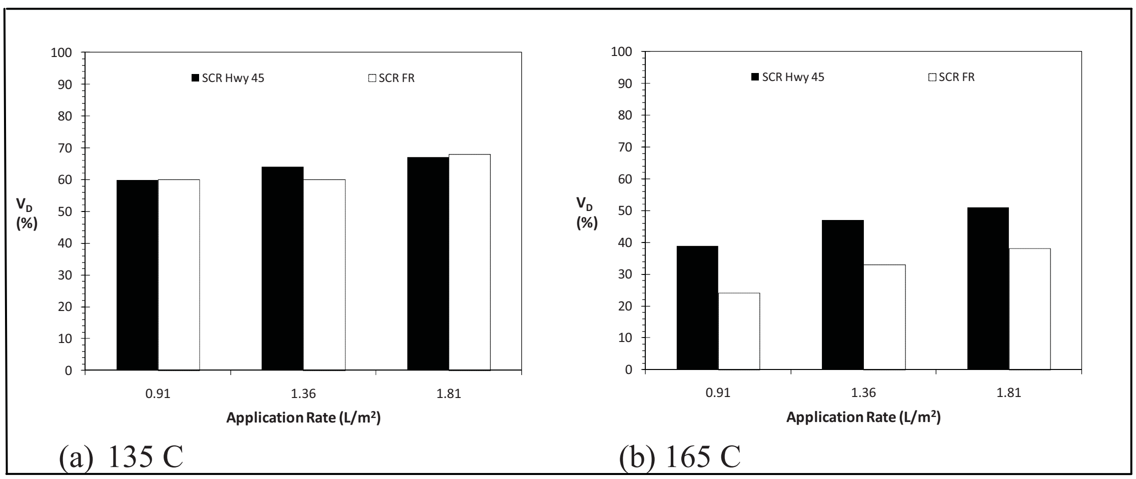
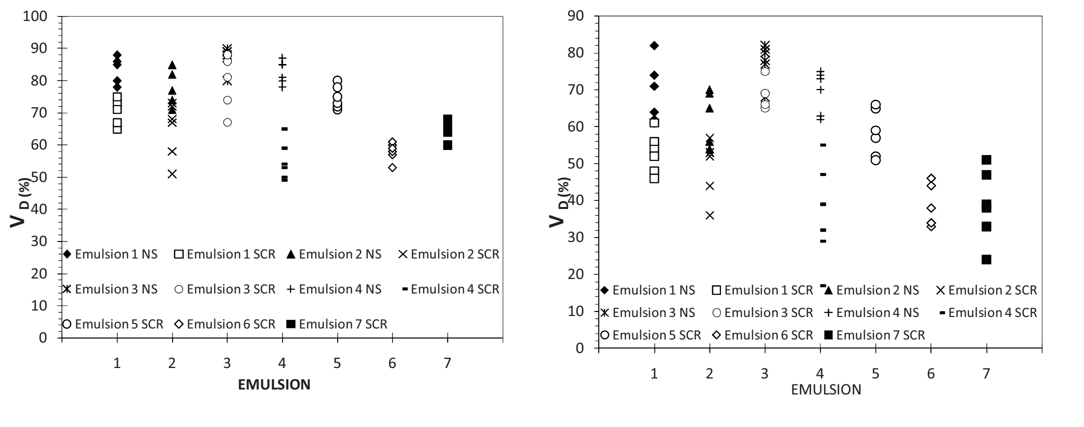


Figure 4.8 Percent Decrease in Viscosity for Emulsion 7

Figure 4.9 shows the range in $V_{D(\%)}$ at 135 C and 165 C for all data points. All data in Figure 4.9 was taken from Figures 4.2 to 4.8. Each series represents six data points; some markers are at the same percent decrease in viscosity. Table 4.1 shows the range in $V_{D(\%)}$ found in Figure 4.9 for each emulsion used in the analysis.



(a) 135 C (b) 165 C

Figure 4.9 Range in Percent Decrease in Viscosity For All Emulsions

Table 4.1

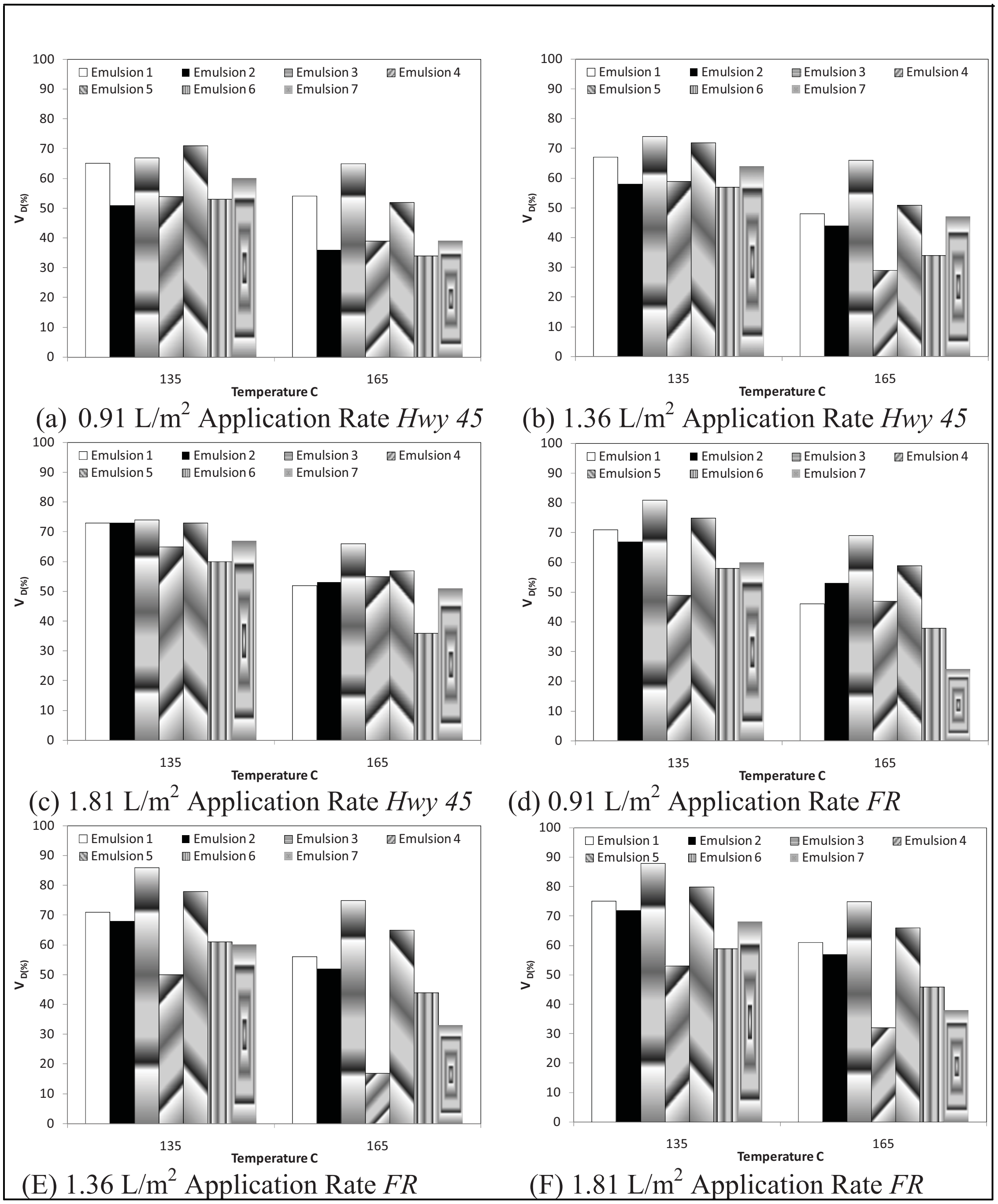
Range in Percent Viscosity Decrease

		Range in $V_{D(\%)}$	
Emulsion No.	***NS or SCR***	**135 C**	**165 C**
1	*NS*	73-88	61-88
	SCR	65-75	46-81
2	*NS*	71-85	54-70
	SCR	51-73	36-57
3	*NS*	87-90	68-82
	SCR	67-88	65-75
4	*NS*	78-87	62-75
	SCR	49-65	17-55
5	*SCR*	71-80	51-66
6	*SCR*	53-61	33-46
7	*SCR*	60-68	24-51

The data in Table 4.1 and Figures 4.2 through 4.9 show all emulsions used in this thesis for surface treatments (either *SCR* or *NS*) reduced viscosity (an expected behavior). The ranges for both *NS* and *SCR* are smaller for 135 C than for 165 C. For both *NS* and *SCR*, overlap occurred at both temperatures.

For the *SCR* specimens, the $V_{D(\%)}$ was, in general, lower than the *NS* specimens. However, due to its larger range in $V_{D(\%)}$, *SCR* specimens tended to show a better relationship for viscosity by taking the excess fully cured emulsion off the surface. When this excess is incorporated, it lowers the viscosity in a manner that would not happen in service. *SCR* specimens are preferred for viscosity testing of surface treated cores. For all emulsions applied to the surface of a core, surface texture tends to be the most variable among the cores. In chip seal design, surface texture is a factor for determining variables such as, application rates for both emulsion and aggregates.

Figure 4.10 shows the overall results for each emulsion at each temperature and application rate with respect to $V_{D(\%)}$. From this Figure, Emulsion 1 had a range of 65 to 75 % decrease in viscosity at 135 C and 45 to 60 % at 165 C. Emulsion 2 had a range of 50 to 75 % decrease in viscosity at 135 C and 35 to 55 % decrease at 165 C. Emulsion 3 had a range of 65 to 85 % decrease in viscosity at 135 C and 65 to 75 % decrease at 165 C. Emulsion 4 had a range of 50 to 65 % decrease in viscosity at 135 C and 20 to 55 % decrease at 165 C. Emulsion 5 had a range of 70 to 80 % decrease in viscosity at 135 C and 50 to 65 % decrease at 165 C. Emulsion 6 had a range of 50 to 60 % decrease in viscosity at 135 C and 35 to 45 % decrease at 165 C. Emulsion 7 had a range of 60 to 70 % decrease in viscosity at 135 C and 25 to 50 % decrease at 165 C.



(a) 0.91 L/m^2 Application Rate *Hwy 45* (b) 1.36 L/m^2 Application Rate *Hwy 45*

(c) 1.81 L/m^2 Application Rate *Hwy 45* (d) 0.91 L/m^2 Application Rate *FR*

(E) 1.36 L/m^2 Application Rate *FR* (F) 1.81 L/m^2 Application Rate *FR*

Figure 4.10 Overall Results for $V_{D(\%)}$

MDOT SS 202 field study tested scraped viscosity specimens (150 mm diameter cores at 6.3 mm slice thickness) using emulsion 3. Figure 4.11 shows the percent decrease in viscosity results. From this figure, treated pavement reduces viscosity, though to a much lesser extent than the laboratory specimens, that were not aged in service. The seal treatments were in service for 18 months at the time of testing.

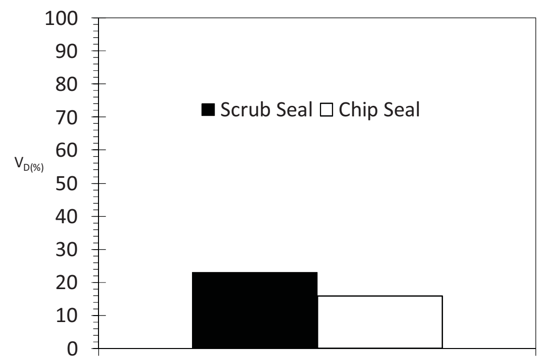


Figure 4.11 *MDOT* SS 202 Field Study on Hwy 17

For performance based specifications, $V_{D(\%)}$ should be considered. Preliminary field data shows that $V_{D(\%)}$ is expected to decrease dramatically when in service. A correlation between field and laboratory specimens will need to be developed to determine a range of $V_{D(\%)}$ to be used in specifications. This will require testing of known materials as a function of aging. The field data provided this thesis from Hwy 17 is introductory data.

4.2.3 Comparison of Measured Viscosity versus Calculated Viscosity

This comparison was conducted to determine if the measured viscosity could be calculated based on volumetric properties of the mixture and viscosity of fully cured emulsion. This analysis was performed for all emulsions based on scraped viscosity (*SCR*) data points from the following steps.

Calculation of Viscosity (*Note: Example values used in these steps were from Hwy 45 test results*)

1. A sample size was found based on the density of each pavement found in section 3.2.2. This value was found to be 249 g for each 6.3 mm slice.
2. From the extraction test result, 4.9 % AC was found to be the average value from extraction tests on *Hwy 45* pavement found in Table B-1 for a 6.3 mm slice. Note: 5.4 % AC was used for *FR* found in Table B-1. These values were used for all calculations for each pavement. Based on the results of this test, it was estimated that 12.2 grams of binder was removed from a *Hwy 45* core slice.
3. Based on the application rate, the amount of emulsion was determined, see Section 3.3.
4. Based on the scraping of cores, the amount of emulsion scraped off was determined. See Appendix A. For this example, 6.8 g of emulsion was used at a 0.91 L/m^2 using Emulsion 1 (Table A-2).
5. Residue values from Table 3.2 were used and applied to determine the amount of emulsion in a core.

$$KK = (G*U)-XX \tag{4-1}$$

Where,

G - Grams of Emulsion at an application rate

U - Residue value

XX - Amount of emulsion scraped of core.

17.5 g*0.699 – 6.8 = 5.4 grams of emulsion penetrated into core slice

6. Viscosity was calculated based on the fully cured emulsion viscosity, control viscosity, weight of binder in sample (Step 2), and weight of emulsion in core (Step 5).

$$(CC*DD+KK*HH)/(CC+KK) \tag{4-2}$$

Where,

CC – Weight of binder in sample

DD – Control viscosity

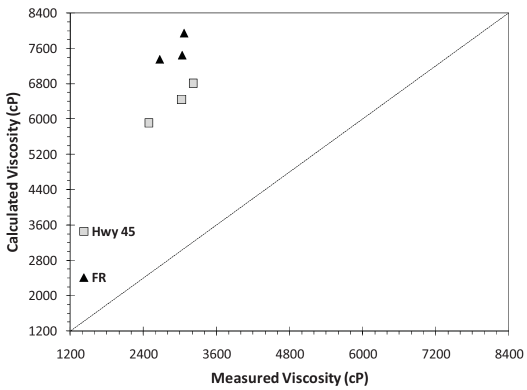
KK – Weight of emulsion in core

HH – Viscosity of fully cured emulsion

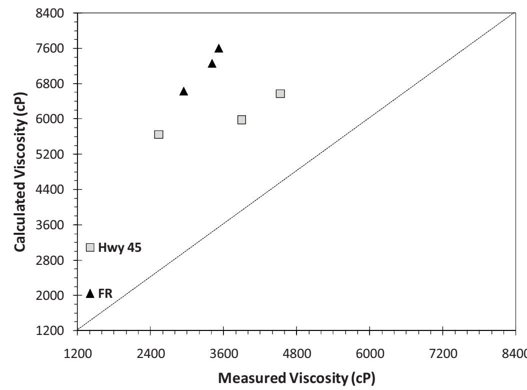
The following example are values from Figure 4.12 (a) in which was taken from *Hwy 45* and using Emulsion 1.

(12.2 g*9216 cP + 5.4 g*1406 cP) / (5.4 g +12.2 g) = 6811 cP

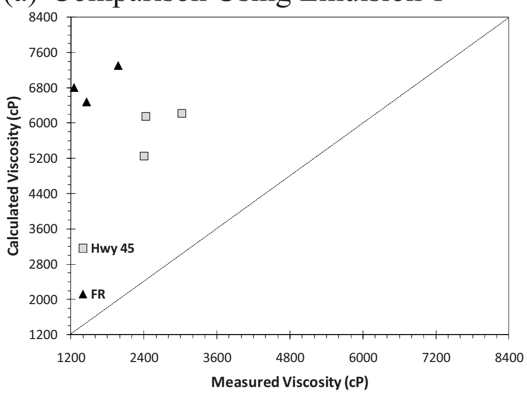
This process was administered to emulsions 1 through 7 for both pavements in order to compare calculated viscosity to measured viscosity. Figures 4.12 and 4.13 show the results of this analysis.



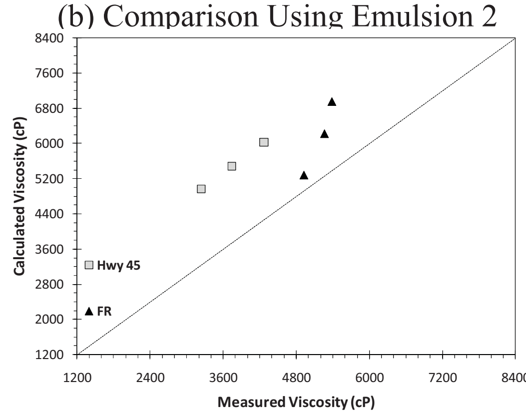
(a) Comparison Using Emulsion 1



(b) Comparison Using Emulsion 2

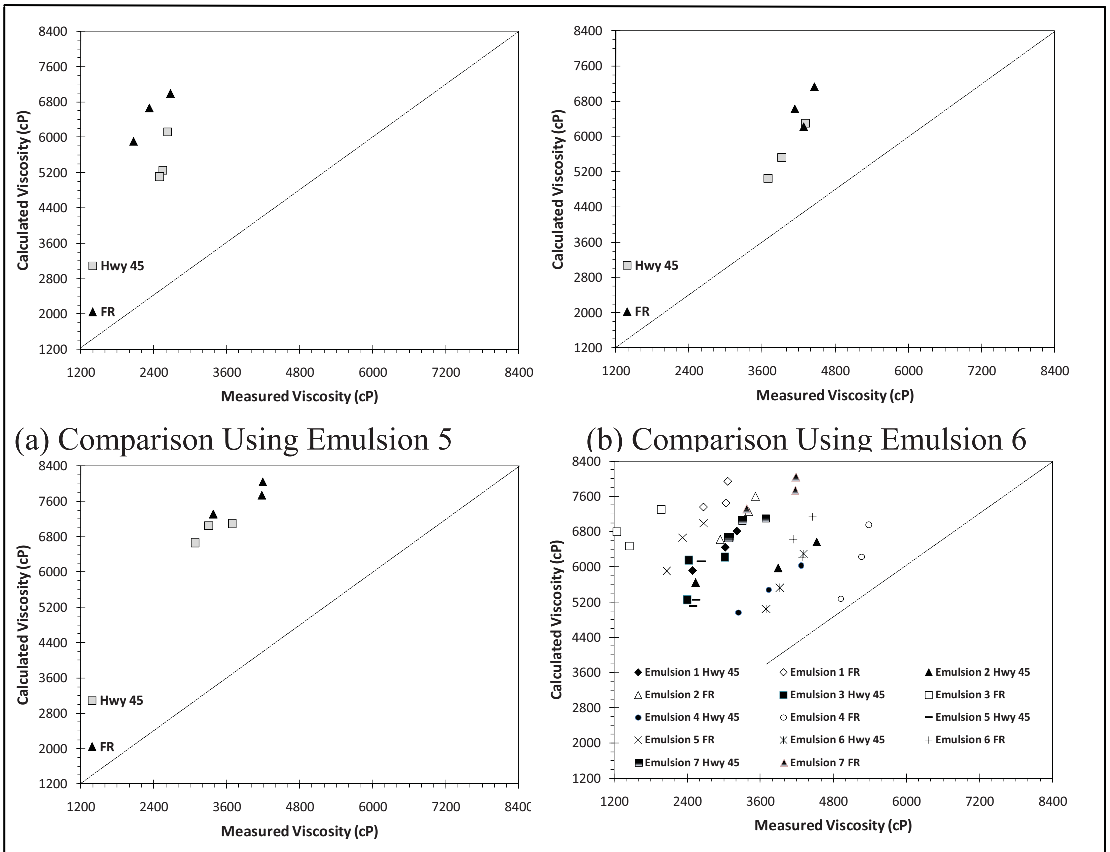


(c) Comparison Using Emulsion 3



(d) Comparison Using Emulsion 4

Figure 4.12 Comparison of Measured and Calculated Viscosity: 1 of 2



(a) Comparison Using Emulsion 5

(b) Comparison Using Emulsion 6

(c) Comparison Using Emulsion 7

(d) Comparison Using All Emulsions

Figure 4.13 Comparison Of Measured and Calculated Viscosity: 2 of 2

From Figures 4.12 and 4.13, the calculated viscosity exceeded the measured viscosity. Emulsion applied to the surface of a pavement decrease the viscosity dramatically more than on a by mixture mass basis. This could be attributed to the residue of emulsion and its characteristics. Based upon the results from Table A-11, Emulsion 1 is composed of a neat asphalt. Emulsion 2, 4, and 5 is composed of a modified polymer asphalt, while emulsion 3 is composed of a tough rubber asphalt base. From these characteristics, emulsion composition and properties are major factors in reducing viscosity of aged pavements.

In developing performance specifications, this knowledge is unnecessary. However an entity should be knowledgeable of the composition and properties of emulsion. These variables effect the chemical reactions between the aged binder and the emulsion.

4.2.4 Paired t-Test

A paired *t*-test was used to determine the effects of the three different application rates used in the scraped condition. There were 42 data points (14 per application rate) representing all scraped viscosity testing. *Note: For any given data point, there were six readings.* Each rate was paired with the other two rates in all possible combinations (i.e. 0.91 and 1.36 L/m^2, 0.91 and 1.81 L/m^2, and 1.36 and 1.81 L/m^2). This analysis was a two tailed *t*-test in which the null hypothesis (H_0) for all t-tests was the mean difference (M_d) equals zero, while the alternative hypothesis (H_a) for all *t*-test were the mean difference (M_d) does not equal to zero. In this analysis, there were three relations observed: Relation 1 compared the 0.91 L/m^2 to 1.36 L/m^2; Relation 2 compared the 1.36 L/m^2 to 1.81 L/m^2; and Relation 3 compared the 0.91 L/m^2 to 1.81 L/m^2. For a relation to consume similarity, the relation should have a "p-value" of greater than 0.05 at both 135 C and 165 C temperatures. The data was analyzed at a 0.05 % level of significance and was performed at 135 C and 165 C. Tables 4.2 and 4.3 provide test results.

Table 4.2

Paired *t*-Test for Viscosity Tests at 135 C: All Data

	Relation 1		Relation 2		Relation 3	
	0.91	**1.36**	**1.36**	**1.81**	**0.91**	**1.81**
Mean	63.00	66.07	66.07	70.00	63.00	70.00
Variance	92.00	91.46	91.46	80.31	92.00	80.31
Standard Deviation	9.59	9.56	9.56	8.96	9.59	8.96
Pearson Correlation	0.969		0.905		0.855	
***t*-statistic**	-4.852		-3.598		-5.198	
P-value	0.0003		0.0032		0.0002	
P-critical Value	2.160		2.160		2.160	
Reject/Accept H_0	Reject		Reject		Reject	

Table 4.3

Paired *t*-Test for Viscosity Tests at 165 C: All Data

	Relation 1		Relation 2		Relation 3	
	0.91	**1.36**	**1.36**	**1.81**	**0.91**	**1.81**
Mean	46.79	47.21	47.21	53.21	46.79	53.21
Variance	160.80	246.03	246.03	148.49	160.80	148.49
Standard Deviation	12.68	15.68	15.68	12.19	12.68	12.19
Pearson Correlation	0.741		0.9053		0.763	
***t*-statistic**	-0.152		-3.225		-2.806	
P-value	0.8818		0.0066		0.0149	
P-critical Value	2.160		2.160		2.160	
Reject/Accept H_0	Accept		Reject		Reject	

From Table 4.2, it can be seen for all application rates at 135 C that there was statistical evidence to indicate that the viscosity change differed with emulsion rate. The higher the application rate resulted in a higher $V_{D(\%)}$ with exception of the 0.91 and 1.36 L/m^2 comparison at 165 C statistical evidence existed that viscosity changed with emulsion application rate.

A paired *t*-test was also conducted for each pavement individually using all emulsions at both 135 C and 165 C. The null and alternative hypothesis' were the same as in the comparisons used in Tables 4.2 and 4.3. The only difference was that there were 21 observations used in which 7 observations were from each application rate. Table 4.4 through 4.7 show these comparisons. At 135 C the trends are the same as when all data was analyzed as a whole, while at 165 C the trends are varied. At 165 C the aged binder is likely being affected more in a relative sense than is the emulsion residue.

Table 4.4

Paired *t*-Test for Viscosity Tests at 135 C for *Hwy 45*

	Relation 1		**Relation 2**		**Relation 3**	
	0.91	**1.36**	**1.36**	**1.81**	**0.91**	**1.81**
Mean	60.14	64.43	64.43	69.29	60.14	69.29
Variance	60.14	46.95	46.95	28.90	60.14	28.90
Standard Deviation	7.75	6.85	6.85	5.38	7.75	5.38
Pearson Correlation	0.958		0.6883		0.598	
***t*-statistic**	-4.954		-2.563		-3.866	
P-value	0.0026		0.0427		0.0083	
P-critical Value	2.447		2.447		2.447	
Accept/Reject H_0	Reject		Reject		Reject	

Table 4.5

Paired *t*-Test for Viscosity Tests at 165 C for *Hwy 45*

	Relation 1		**Relation 2**		**Relation 3**	
	0.91	**1.36**	**1.36**	**1.81**	**0.91**	**1.81**
Mean	45.57	45.57	45.57	52.86	45.57	52.86
Variance	133.62	144.29	144.29	80.48	133.62	80.48
Standard Deviation	11.56	12.01	12.01	8.97	11.56	8.97
Pearson Correlation	0.841		0.689		0.750	
***t*-statistic**	0		-2.208		-5.519	
P-value	1		0.0694		0.0454	
P-critical Value	2.447		2.447		2.447	
Accept/Reject H_0	Accept		Accept		Reject	

Table 4.6

Paired *t*-Test for Viscosity Tests at 135 C for *FR*

	Relation 1		**Relation 2**		**Relation 3**	
	0.91	**1.36**	**1.36**	**1.81**	**0.91**	**1.81**
Mean	65.86	67.71	67.71	70.71	65.86	70.71
Variance	120.14	144.90	144.90	143.90	120.14	143.90
Standard Deviation	10.96	12.04	12.04	12.00	10.96	12.00
Pearson Correlation	0.991		0.968		0.985	
***t*-statistic**	-2.635		-2.646		-5.666	
P-value	0.0388		0.0382		0.0013	
P-critical Value	2.447		2.447		2.447	
Reject/Accept H_0	Reject		Reject		Reject	

Table 4.7

Paired t-Test for Viscosity Tests at 165 C for *FR*

	Relation 1		**Relation 2**		**Relation 3**	
	0.91	**1.36**	**1.36**	**1.81**	**0.91**	**1.81**
Mean	48.00	48.86	48.86	53.57	48.00	53.57
Variance	211.33	382.48	382.48	240.95	211.33	240.95
Standard Deviation	14.54	19.56	19.56	15.52	14.54	15.52
Pearson Correlation	0.697		0.986		0.783	
***t*-statistic**	-0.1614		-2.499		-1.482	
P-value	0.8771		0.0466		0.1889	
P-critical Value	2.447		2.447		2.447	
Reject/Accept H_0	Accept		Reject		Accept	

4.2.5 Comparison of Asphalt Penetrated to Percent Decrease in Viscosity

This comparison was used to determine a relationship between the amount of asphalt binder penetrated (% AC penetrated) and $V_{D(\%)}$. The % AC penetrated is the amount of fully cured emulsion penetrating the pavement surface, thus providing rejuvenation. All scraped viscosity points were used for this analysis for all application rates, both pavements, and both temperatures. The following procedure was incorporated and used to develop Figure 4.14.

Comparison Procedure

1. $V_{D(\%)}$ was found by equation 2.2 for all application rates using emulsions 1 to 7 on both pavements.
2. The amount of fully cured emulsion in a 6.3 mm core slice and amount of AC in an untreated core was found in accordance to the procedure developed in section 4.2.3.

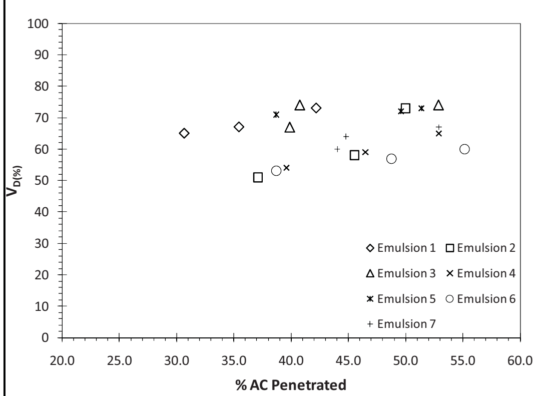
3. Percent of Asphalt Content penetrated (% AC Penetrated) was found through the following equation.

   $$\{KK/(KK+CC)\}100 \tag{4-3}$$

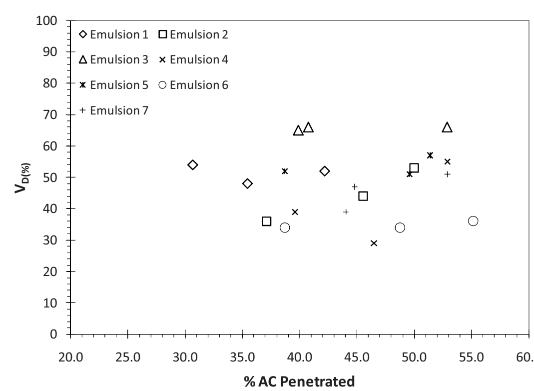
   Example (Using *Hwy 45* volumetrics using Table A-2 for the 0.91 L/m^2)

   $\{5.4/(12.2+5.4)\}*100 = 30.7$ %

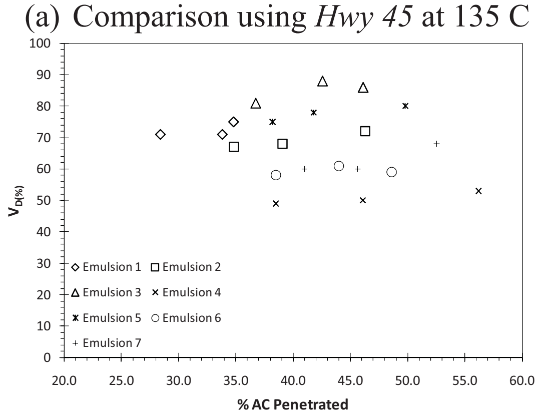
   30.7 % AC Penetrated was found in 0.91 L/m^2 sample using Emulsion 1 in which is the x-coordinate. The y-coordinate is the $V_{D(\%)}$. For the example, the y-coordinate is 65%. *Note: At the 165 C temperature, % AC penetrated (x-coordinate) was the same as determined in the 135 C temperature.*



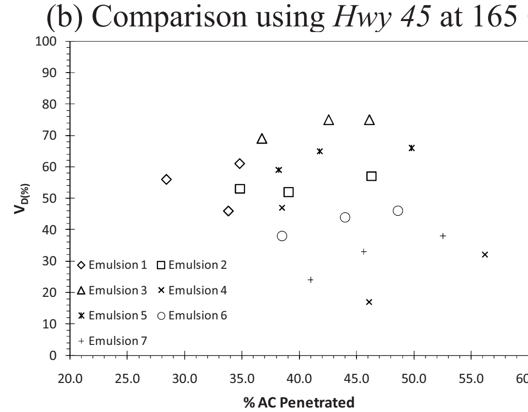
(a) Comparison using *Hwy 45* at 135 C



(b) Comparison using *Hwy 45* at 165 C



(c) Comparison using *FR* at 135 C



(d) Comparison using *FR* at 165 C

Figure 4.14 Comparison of % AC Penetrated to $V_{D(\%)}$

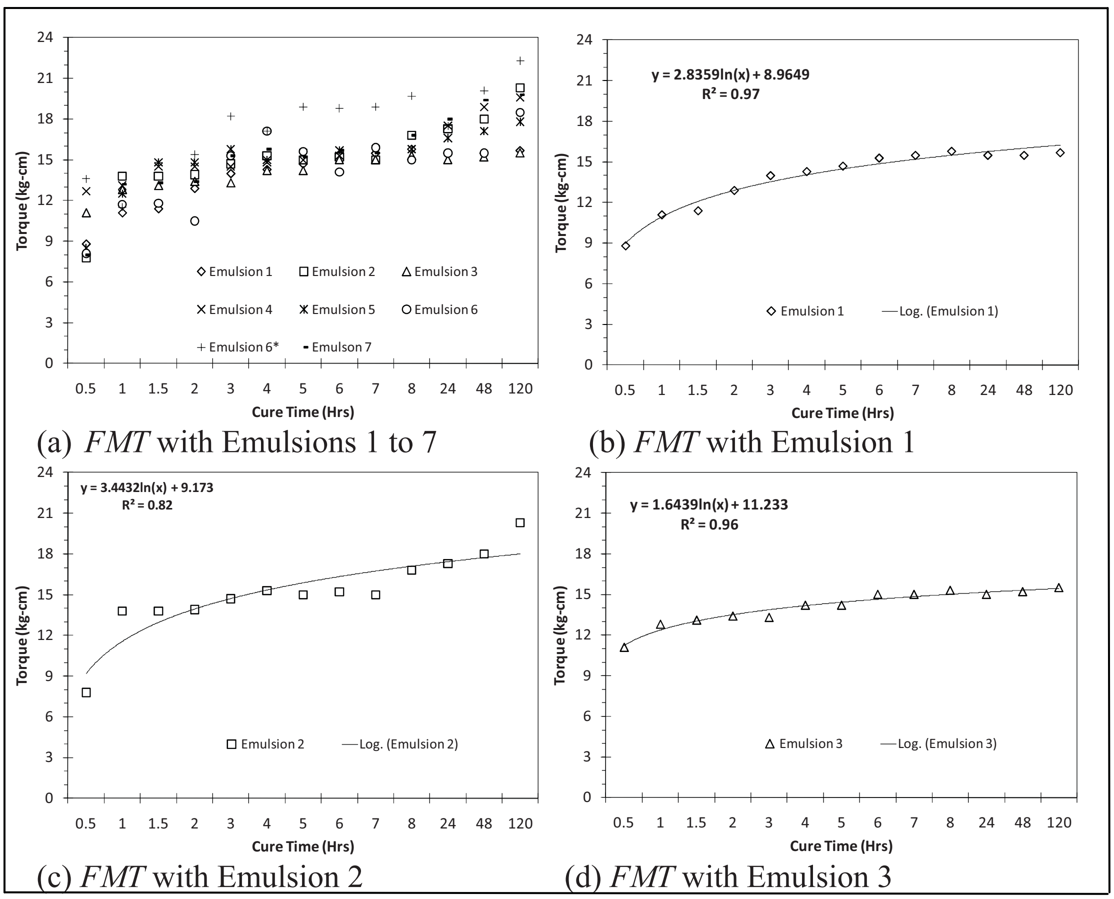
There is no correlation between $V_{D(\%)}$ and % AC Penetrated. *Note: For all emulsions, the symbol with the lowest % AC penetrated is the 0.91 L/m^2 application rate, and the symbol with the highest % AC penetrated is the 1.81 L/m^2.* Emulsion 4 has relatively high % AC Penetrated but has low $V_{D(\%)}$; an expected behavior. Emulsion 3 has at to near the highest $V_{D(\%)}$ for the individual cases considered yet is not the highest % AC penetrated Figure 4.14 does show that emulsions act differently with different pavements. As can be expected with the pavements studied, products such as emulsion 3, are the best for use with aged pavements (producer's claim supported by the test data). Emulsions 1 and 2 are typically used during the early portion of a pavements service life.

4.3 Frosted Marble Test Results

The *FMT* was used to evaluate the portion above the original pavement surface and the strength of each emulsion related to chip retention for surface treatment applications. Typically, the use of the *FMT* would be as an indication for fast breaking emulsions. The torque value will "jump" to a certain number (not known due to the consistency of each emulsion type), indicating a relatively strong binder. In practice, the shape and slope of the line are evaluated which would determine if an emulsion would break rapidly which would not age early in its service life. For ideal situations, the line should be flat to gradually sloping, meaning that the emulsion has cured and developed its strength through the course of cure time. However, the *FMT* does not have a "high strength" criteria to meet. When using this test, low torque values throughout indicate that binder is not curing properly.

4.3.1 FMT Results – Moisture Content Not Measured

The *FMT* was used with emulsions 1 to 7 in which 91 data points were collected during testing. Each of these data points are the average value of 15 torqued marbles. For each data point with corresponding curing time, engineering judgment was used to determine the validity of each result from each torque marble. Figures 4.15 and 4.16, provide the results from the *FMT*. *Note: For emulsion 6, an (*) denotes that an experienced operator with notable experience with the equipment conducted the test.*



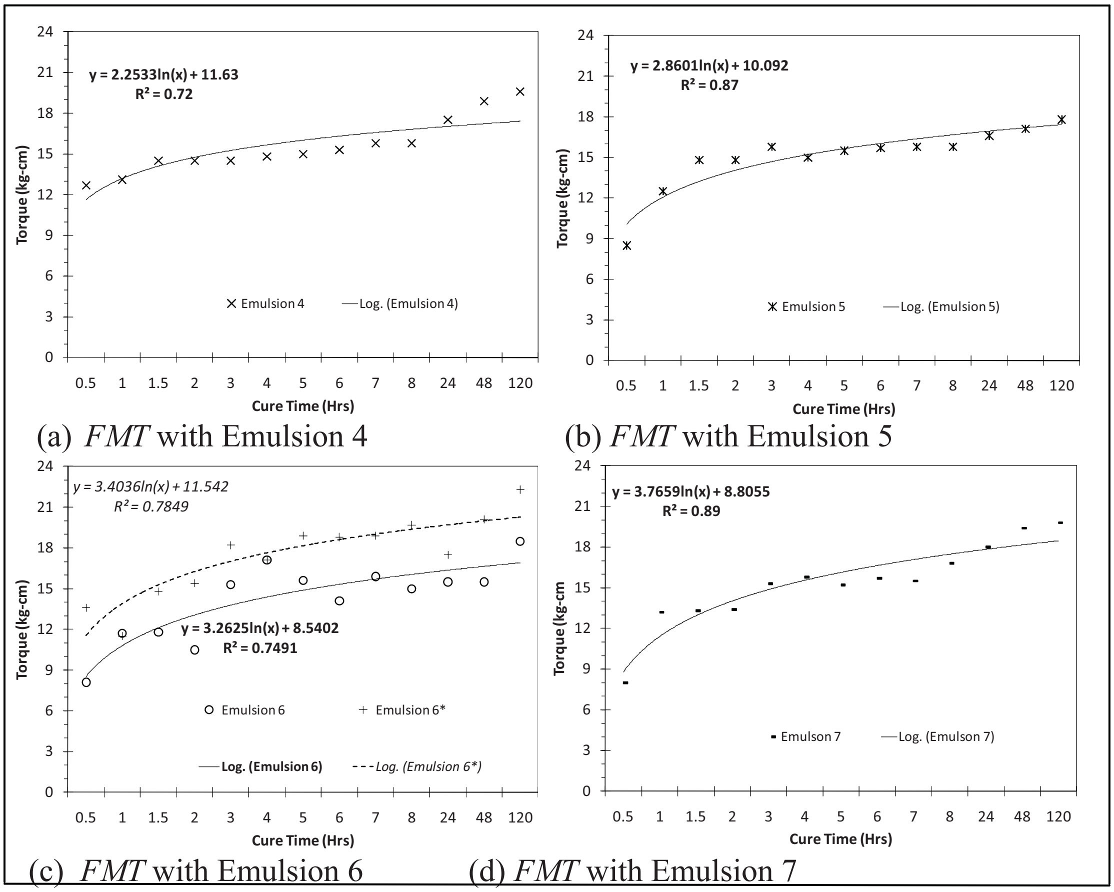
(a) *FMT* with Emulsions 1 to 7

(b) *FMT* with Emulsion 1

(c) *FMT* with Emulsion 2

(d) *FMT* with Emulsion 3

Figure 4.15 *FMT* Results: 1 of 2



(a) *FMT* with Emulsion 4 (b) *FMT* with Emulsion 5

(c) *FMT* with Emulsion 6 (d) *FMT* with Emulsion 7

Figure 4.16 *FMT* Results: 2 of 2

From these Figures, it is shown that as cure time increases, the strength of the emulsion increases as expected. Emulsion 1 does not have the strength as compared to some of the other emulsions. However, it remains relatively constant after the strength of the emulsion has occurred, therefore, the seal would be considered durable in early stages of its life after application. Emulsion 2 shows that the binder cured similar to emulsion 1; curing happened slowly. This emulsion maintains a relatively flat line though the trend for the values is noticeably higher than emulsion 1. Of all emulsions, emulsion 3 is considered the most ideal condition. This emulsion cures quick and maintains strength. The low torque values can be attributed to the oil based emulsion. This creates a slip plane between the marble and the emulsion. Emulsion 5 starts low but cures at a fast rate and has similar properties as emulsion 4. Emulsions 6 and 7 have the highest slope, which would indicate that they are not developing a high rate of cure. These emulsions continue to cure and are difficult to achieve its nominal strength properties.

Emulsion 4 provided the highest strength at 0.5 hour, while emulsions 2 and 7 provide the lowest strength at 0.5 hour. At 120 hours, emulsions 2, 4, 5, 6, and 7 are providing the highest strength (i.e. around 20 kg-cm) at this cure time, while emulsions 1 and 3 are providing the lowest strength (i.e. around 15.5 kg-cm).

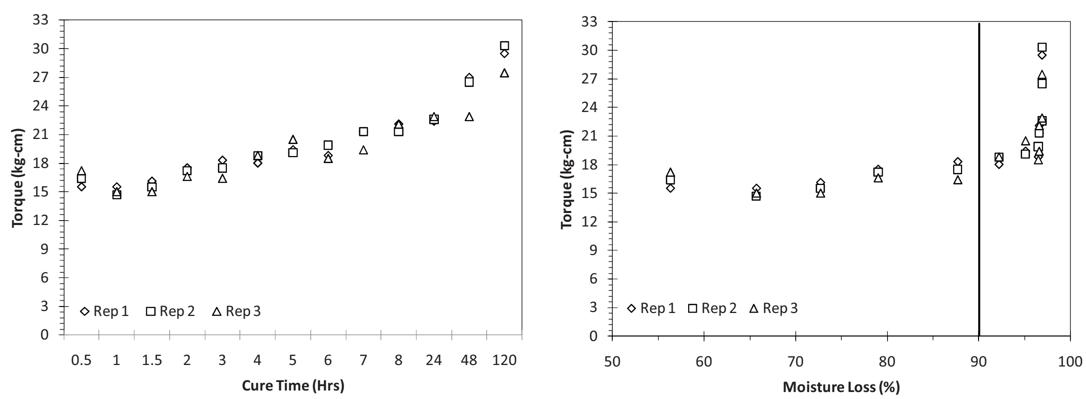
Ranking the emulsions due to performance was based upon the slope of the trend line. The lowest slope received a ranking of (1) and the highest a (7). Based from the results of the *FMT*, it was determined that Emulsion 3 provided the lowest slope and thus a ranking of 1. The ranking of emulsions based upon *FMT* results are as follows: Emulsion 4 (2), Emulsion 1 (3), Emulsion 5 (4), Emulsion 6 (5), Emulsion 2 (6), and Emulsion 7 (7).

The *FMT* is not recommended for performance based specifications at the present time due to the variability between the emulsions and operators. However, the *FMT* is a great tool for comparison purposes and determining how an emulsion will behave. It is also useful for establishing trends which may be incorporated into specifications.

4.3.2 FMT Results – Moisture Content Measured

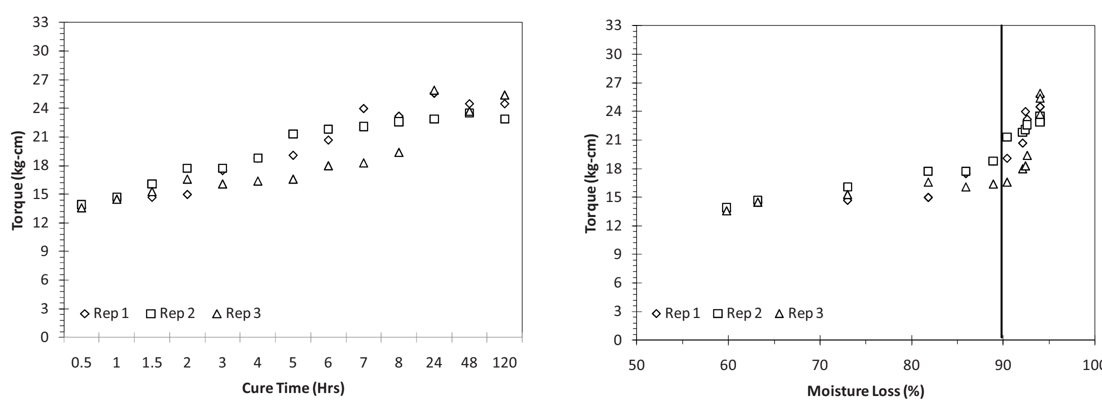
Selected *FMT*'s were considered in comparing the effect of moisture loss of an emulsion to the aggregate retention strength. Three replicates of each data point were used for the torque value and two replicates for each data point were used for wc_{loss}. For any given data point (averaged value of 15 torque marbles), the two highest and lowest values were taken out of calculations.

Moisture Loss was calculated by equation 3.3. *All values used in example were taken from emulsion 1 at 0.5 hour cure time.* Figures 4.16 to 4.19 show the relationship between cure time versus torque, and moisture loss versus torque.



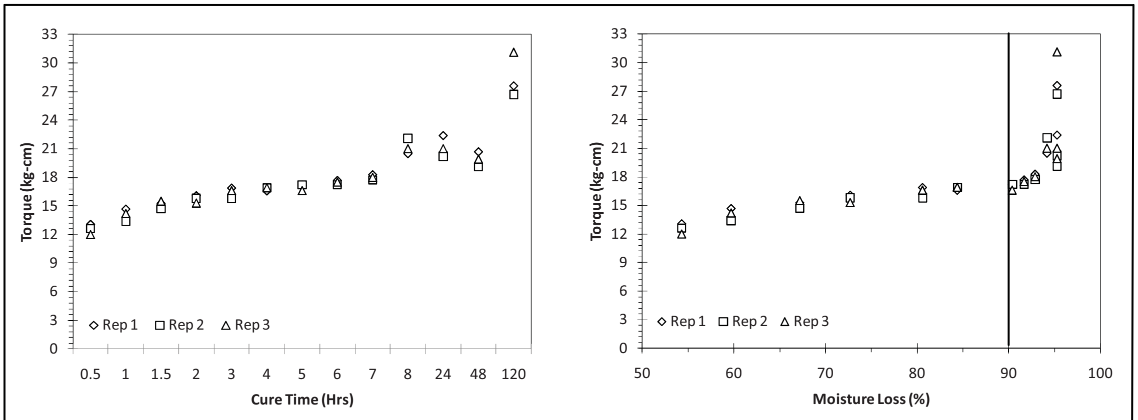
(a) Emulsion 8 *FMT* Results (b) Emulsion 8 *FMT* vs. wc_{LOSS}

Figure 4.17 *FMT* Results for Emulsion 8



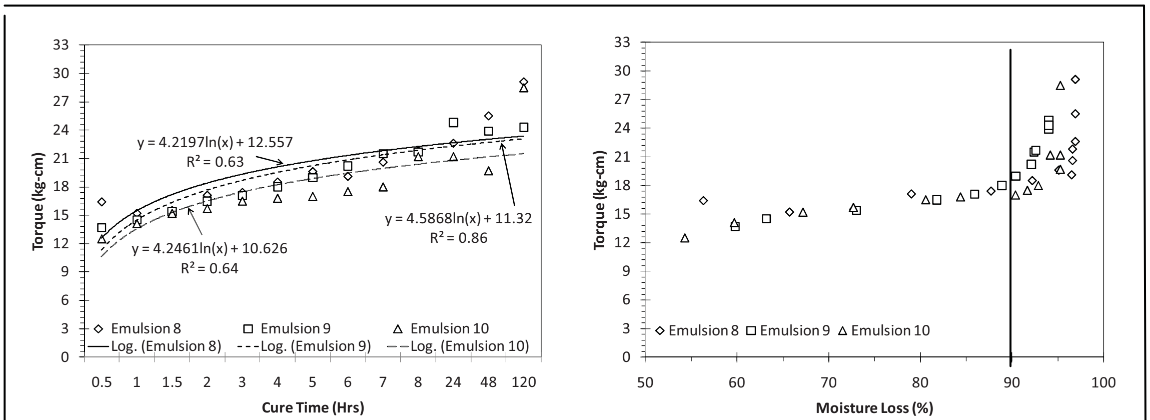
(a) Emulsion 9 FMT Results (b) Emulsion 9 FMT vs. wc_{LOSS}

Figure 4.18 *FMT* Results for Emulsion 9



(a) Emulsion 10 FMT Results (b) Emulsion 10 FMT vs wc_{LOSS}

Figure 4.19 *FMT* Results for Emulsion 10



(a) Emulsions 8 to 10: FMT Results (b) Emulsions 8 to 10: FMT vs wc_{LOSS}

Figure 4.20 Averaged *FMT* Results for Emulsions 8 to 10

Based on the results from Figures 4.16 through 4.20, moisture loss of an emulsion is highly dependent upon when the emulsion breaks and undergoes more of an asphalt characteristic. The integrity of the emulsion residue evaluates performance. As cure time increases, torque and moisture loss increases. From these results, 90% of moisture loss is considered a good value in determining when the emulsion undergoes asphalt characteristics and could be used for performance specifications. This binder is much stiffer, thus providing it strength to the marble or aggregate particle. From the results of this test, Emulsion 9, reached 90 % moisture loss the quickest and Emulsion 8 was the slowest. This data could be further developed into guidance in opening a pavement to traffic under a given set of conditions.

4.4 Overall Ranking of Emulsions

Ranking of emulsions were based only upon the performance of the tests administered. Emulsions vary between product as well as type of pavement that it is applied to. Results based upon strength of emulsion was only based upon *FMT* results. Different aggregate-emulsion combinations will behave differently which was not considered in this thesis. The rankings from $V_{D(\%)}$ and *FMT* were averaged. The lowest average was considered the "best" emulsion and given (1). The highest average was considered the "worst" and given a (7). Table 4.8 shows the rankings of the emulsion.

Table 4.8

Rankings of Emulsion

Emulsion Number	Ranking
Emulsion 3	1
Emulsion 1	2-3
Emulsion 5	2-3
Emulsion 4	4
Emulsion 2	5-6
Emulsion 7	5-6
Emulsion 6	7

CHAPTER V

CONCLUSIONS

All objectives of this thesis were met. The information gained can be used as a starting point for determining performance specifications for surface treatments. In using performance specifications, percent decrease in viscosity ($V_{D(\%)}$) and moisture loss (wc_{LOSS}) of an emulsion can be used as a part of specifying emulsions for surface treatments. Emulsions used as surface treatments for asphalt pavements do reduce binder viscosity as can be seen in Section 4.2. The performance of the treatment is highly dependent upon the characteristics and properties of the asphalt pavement.

For $V_{D(\%)}$, it is difficult to determine a certain range for each emulsion to be used in practice, which should be determined before implementing specifications. There were differences between field and laboratory specimens which is to be expected due to the many factors that have occurred with the samples produced from the field. For specifications, each emulsion used for this testing should meet a certain range which is yet to be determined. Field data coupled with laboratory aged specimens should shed light on this behavior.

Through testing, it was determined that scraping the excess residue off the surface of a core would result in a sample that would be more representative of an in-service pavement from the standpoint of effect on the aged surface. From this, Emulsion 1 had a range of 65 to 75 % decrease in viscosity at 135 C and 45 to 60 % at 165 C. Emulsion 2 had a range of 50 to 75 % decrease in viscosity at 135 C and 35 to 55 % decrease at 165 C. Emulsion 3 had a range of 65 to 85 % decrease in viscosity at 135 C and 65 to 75 % decrease at 165 C. Emulsion 4 had a range of 50 to 65 % decrease in viscosity at 135 C and 20 to 55 % decrease at 165 C. Emulsion 5 had a range of 70 to 80 % decrease in viscosity at 135 C and 50 to 65 % decrease at 165 C. Emulsion 6 had a range of 50 to 60 % decrease in viscosity at 135 C and 35 to 45 % decrease at 165 C. Emulsion 7 had a range of 60 to 70 % decrease in viscosity at 135 C and 25 to 50 % decrease at 165 C.

There is not a relationship between measured and calculated percent decrease in viscosity. The viscosity values obtained depended highly upon the chemical properties of the emulsion. Tough rubber base asphalt emulsions (Emulsion 3) tend to decrease the viscosity in aged pavements more than neat asphalt or polymer modified asphalt emulsions.

The pared *t*-test showed a statistically significant change in viscosity for *SCR* specimens in all cases at 135 C. At 165 C, the test sometimes detected differences but not others. At 165 C the aged binder is likely being affected more in a relative sense than is the emulsion residue.

Moisture loss of emulsions should be considered in performance based specifications. At 90% of moisture loss, the emulsion undergoes a transition and becomes more of an asphalt. This provides the emulsion with stiffness which is crucial to chip retention. At this percentage, the emulsion has nearly fully cured and torque values are the highest resulting in good chip retention. In practice, this could be used to determine when to release traffic onto the treatment and have less loose aggregate.

The *FMT* is not recommended for performance specifications at present time due to the variability of emulsions and operators. This test is sensitive to the operators as well as the position in the environmental chamber. Specimens in warmer positions of the environmental chamber tend to produce higher torque values and cure rates than ones placed in cooler positions when plotted as a function of time. This test does give valuable information on how emulsions cure, behave, and it gives a good indication of strength, which is useful for both producers and customers. Most emulsions tested, cured within a couple of hours and maintained strength.

Overall, Emulsion 3 performed the best among using viscosity and frosted marble testing. This emulsion tended to have the most decrease in viscosity, and quick cure rate. Emulsion 6 performed the worst among the emulsions used. Rejuvenation, chip retention, $V_{D(\%)}$, and moisture loss are highly dependent upon combinations and properties of emulsion, pavement, and aggregates (which were not evaluated). The tests that were conducted in this thesis can serve as a basis or another aspect towards developing performance based specifications in the State of Mississippi.

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APPENDIX A

VISCOSITY TEST DATA

Table A.1

Pavement Viscosity Characteristics with No Emulsion Application

		Viscosity at Depth of Cutting (cP)					
		6.3 mm		**9.5 mm**		**12.5 mm**	
Pavement Type	**Reading**	**135 C**	**165 C**	**135 C**	**165 C**	**135 C**	**165 C**
Hwy 45	1	9125	1375	8962	1487	9787	2750
	2	9100	1363	9012	1500	10000	2775
	3	9125	1375	9000	1500	10000	2738
	Avg	**9117**	**1371**	**8991**	**1496**	**8967**	**1467**
FR	1	10787	1450	6400	1337	4900	738
	2	10800	1450	6378	1350	4913	738
	3	10800	1438	6375	1375	4925	725
	4	11013	1387	6775	1087	--	--
	5	11000	1387	6738	1075	--	--
	6	11013	1400	6800	1087	--	--
	Avg	**10902**	**1419**	**6578**	**1219**	**4913**	**734**
Hwy 45	1	9550	1200	--	--	--	--
	2	9488	1213	--	--	--	--
	3	9500	1225	--	--	--	--
	4	9138	1200	--	--	--	--
	5	9100	1188	--	--	--	--
	6	9038	1200	--	--	--	--
	Avg	**9302**	**1204**	--	--	--	--
Hwy 45	1	9230	1375	--	--	--	--
	2	9267	1375	--	--	--	--
	3	9187	1388	--	--	--	--
	Avg	**9228**	**1379**	--	--	--	--
FR	1	10437	1463	--	--	--	--
	2	10525	1475	--	--	--	--
	3	10437	1463	--	--	--	--
	Avg	**10466**	**1467**	--	--	--	--
FR	1	10225	1650	--	--	--	--
	2	10337	1550	--	--	--	--
	3	10288	1587	--	--	--	--
	Avg	**10283**	**1596**	--	--	--	--

Table A.2

Viscosity Characteristics of Pavements with Emulsion 1 Applied (6.3 mm)

Pavement (Application Rate) (L/m^2)	**Viscosity at 6.3 mm (cP) *NS* Specimens**			**Viscosity At 6.3 mm (cP) *SCR* Specimens**		
	Reading	**135 C**	**165 C**	**Reading**	**135 C**	**165 C**
Hwy 45	1	2362	475	1	3288	613
(0.91)	2	2375	488	2	3275	600
	3	2325	488	3	3300	613
	4	2600	513	4	3150	613
-12.2-	5	2613	550	5	3138	600
--6.8--	6	2600	513	6	3150	600
---5.4---	**Avg**	**2479**	**505**	**Avg**	**3217**	**606**
Hwy 45	1	2075	463	1	3000	663
(1.36)	2	2038	450	2	3025	650
	3	2025	450	3	3025	663
	4	2000	500	4	3038	713
-17.8-	5	2025	500	5	3038	700
--11.1--	6	2025	500	6	3025	700
---6.7---	**Avg**	**2032**	**477**	**Avg**	**3025**	**682**
Hwy 45	1	1350	363	1	2525	775
(1.81)	2	1350	375	2	2525	775
	3	1350	363	3	2538	763
	4	1338	313	4	2450	500
-23.3-	5	1313	313	5	2438	500
--14.4--	6	1288	313	6	2450	513
---8.9---	**Avg**	**1332**	**340**	**Avg**	**2488**	**638**
FR	1	2138	513	1	2813	625
(0.91)	2	2125	525	2	2800	613
	3	2138	513	3	2813	625
	4	2175	600	4	3262	1000
-12.2-	5	2163	675	5	3275	1000
--5.5--	6	2175	663	6	3262	1000
---6.7---	**Avg**	**2152**	**582**	**Avg**	**3038**	**811**
FR	1	1375	388	1	3050	650
(1.36)	2	1363	388	2	3050	650
	3	1375	388	3	3075	650
	4	1775	488	4	3075	650
-17.8-	5	1750	488	5	3088	650
--12.6--	6	1788	475	6	3075	650
---5.2---	**Avg**	**1571**	**436**	**Avg**	**3069**	**650**
FR	1	1200	288	1	2838	550
(1.81)	2	1200	288	2	2838	550
	3	1188	288	3	2825	563
	4	1375	263	4	2413	613
-23.3-	5	1350	263	5	2400	613
--16.3--	6	1350	263	6	2413	600
---7.0---	**Avg**	**1277**	**276**	**Avg**	**2621**	**582**

-Value- indicates grams of fully cured emulsion in SCR specimens.
--Value-- indicates grams of fully cured emulsion removed from SCR specimens.
---Value--- indicates grams of fully cured emulsion remaining in SCR Specimens.

Table A.3

Viscosity Characteristics of Pavements with Emulsion 2 Applied (6.3 mm)

Pavement (Application Rate) (L/m^2)	Viscosity at 6.3 mm (cP) *NS* Specimens Reading	135 C	165 C	Viscosity At 6.3 mm (cP) *SCR* Specimens Reading	135 C	165 C
Hwy 45	1	2112	513	1	4488	875
(0.91)	2	2100	500	2	4475	862
	3	2112	513	3	4475	875
	4	2162	713	4	4588	813
-11.9-	5	2150	700	5	4575	825
--4.7--	6	2150	700	6	4575	825
---7.2---	**Avg**	**2131**	**607**	**Avg**	**4529**	**846**
Hwy 45	1	1413	300	1	3787	638
(1.36)	2	1400	350	2	3775	638
	3	1388	338	3	3787	638
	4	3475	837	4	3987	838
-17.4-	5	3463	837	5	4025	850
--7.2--	6	3463	825	6	4000	838
---10.2---	**Avg**	**2434**	**581**	**Avg**	**3894**	**740**
Hwy 45	1	1400	463	1	2625	550
(1.81)	2	1388	450	2	2650	525
	3	1388	450	3	2625	538
	4	1362	338	4	2438	713
-22.7-	5	1362	338	5	2425	700
--10.5--	6	1375	350	6	2438	700
---12.2---	**Avg**	**1379**	**398**	**Avg**	**2534**	**621**
FR	1	2275	513	1	3112	600
(0.91)	2	2263	500	2	3100	613
	3	2275	500	3	3100	600
	4	3775	813	4	3950	813
-11.9-	5	3888	813	5	3913	813
--4.9--	6	3800	800	6	3950	813
---7.0---	**Avg**	**3046**	**657**	**Avg**	**3520**	**709**
FR	1	1962	587	1	3075	638
(1.36)	2	1975	550	2	3050	638
	3	1950	550	3	3050	650
	4	1725	475	4	3787	800
-17.4-	5	1750	500	5	3763	800
--9.0--	6	1750	475	6	3738	813
---8.4---	**Avg**	**1852**	**523**	**Avg**	**3410**	**723**
FR	1	1663	550	1	2813	600
(1.81)	2	1650	550	2	2825	588
	3	1663	563	3	2813	600
	4	1538	375	4	3075	688
-22.7-	5	1525	350	5	3075	688
--11.4--	6	1538	375	6	3075	700
---11.3---	**Avg**	**1596**	**461**	**Avg**	**2946**	**644**

-Value- indicates grams of fully cured emulsion in SCR specimens.
--Value-- indicates grams of fully cured emulsion removed from SCR specimens.
---Value--- indicates grams of fully cured emulsion remaining in SCR Specimens.

Table A.4

Viscosity Characteristics of Pavements with Emulsion 3 Applied (6.3 mm)

Pavement (Application Rate) (L/m^2)	**Viscosity at 6.3 mm (cP) *NS* Specimens**			**Viscosity At 6.3 mm (cP) *SCR* Specimens**		
	Reading	**135 C**	**165 C**	**Reading**	**135 C**	**165 C**
Hwy 45	1	1162	163	1	3158	425
(0.91)	2	1125	163	2	3175	413
	3	1150	163	3	3188	425
	4	1263	300	4	2862	513
-11.8-	5	1275	300	5	2875	500
--3.7--	6	1263	300	6	2862	500
---8.1---	**Avg**	**1206**	**232**	**Avg**	**3019**	**463**
Hwy 45	1	1000	300	1	2400	350
(1.36)	2	1000	287	2	2450	375
	3	1000	325	3	2400	375
	4	1000	287	4	2450	525
-17.2-	5	1050	287	5	2438	525
--8.8--	6	1025	300	6	2438	513
---8.4---	**Avg**	**1013**	**298**	**Avg**	**2429**	**444**
Hwy 45	1	1100	350	1	2362	413
(1.81)	2	1125	350	2	2350	400
	3	1100	375	3	2350	400
	4	950	225	4	2438	488
-22.6-	5	1000	225	5	2450	475
--8.9--	6	950	225	6	2450	488
---13.7---	**Avg**	**1038**	**292**	**Avg**	**2400**	**444**
FR	1	1237	300	1	1987	438
(0.91)	2	1212	300	2	2000	450
	3	1200	300	3	1987	438
	4	3100	650	4	1950	488
-11.8-	5	3100	650	5	1962	500
--4.2--	6	3100	638	6	1950	488
---7.6---	**Avg**	**2158**	**475**	**Avg**	**1973**	**467**
FR	1	1013	300	1	1375	338
(1.36)	2	1025	275	2	1400	350
	3	1037	287	3	1375	338
	4	1000	300	4	1525	425
-17.2-	5	1012	313	5	1513	425
--6.0--	6	988	300	6	1525	400
---11.2---	**Avg**	**1013**	**296**	**Avg**	**1452**	**379**
FR	1	1138	275	1	1175	425
(1.81)	2	1125	275	2	1187	425
	3	1112	275	3	1175	413
	4	1188	300	4	1325	313
-22.6-	5	1188	300	5	1313	313
--12.9--	6	1200	313	6	1300	313
---9.7---	**Avg**	**1159**	**290**	**Avg**	**1246**	**367**

-Value- indicates grams of fully cured emulsion in SCR specimens.
--Value-- indicates grams of fully cured emulsion removed from SCR specimens.
---Value--- indicates grams of fully cured emulsion remaining in SCR Specimens.

Table A.5

Viscosity Characteristics of Pavements with Emulsion 3 Applied (9.5 and 12.7 mm)

Pavement (Application Rate) (L/m^2)	**Viscosity at 9.5 mm (cP) *NS* Specimens**			**Viscosity At 12.7 mm (cP) *NS* Specimens**		
	Reading	**135 C**	**165 C**	**Reading**	**135 C**	**165 C**
FR (0.91)	1	1769	763	1	2375	712
	2	1757	688	2	2300	712
	3	1763	763	3	2350	712
	4	1663	625	4	2350	700
	5	1612	650	5	2362	700
	6	1600	625	6	2362	687
	Avg	**1694**	**686**	**Avg**	**2350**	**704**
FR (1.36)	1	1313	325	1	1663	325
	2	1313	325	2	1612	350
	3	1300	313	3	1600	323
	4	1425	313	4	1563	363
	5	1425	300	5	1530	350
	6	1413	300	6	1563	363
	Avg	**1365**	**312**	**Avg**	**1588**	**346**

Table A.6

Viscosity Characteristics of Pavements with Emulsion 4 Applied (6.3 mm)

Pavement (Application Rate) (L/m^2)	**Viscosity at 6.3 mm (cP) *NS* Specimens**			**Viscosity At 6.3 mm (cP) *SCR* Specimens**		
	Reading	**135 C**	**165 C**	**Reading**	**135 C**	**165 C**
Hwy 45	1	1813	463	1	4275	850
(0.91)	2	1800	463	2	4275	850
	3	1763	463	3	4263	838
	4	1875	500	4	4275	762
-12.2-	5	1825	513	5	4275	762
--4.2--	6	1825	513	6	4250	775
---8.0---	**Avg**	**1817**	**486**	**Avg**	**4269**	**806**
Hwy 45	1	1375	375	1	3625	875
(1.36)	2	1350	375	2	3600	875
	3	1337	375	3	3625	875
	4	1463	325	4	3875	1000
-17.8-	5	1500	325	5	3850	988
--7.2--	6	1475	325	6	3875	988
---10.6---	**Avg**	**1416**	**350**	**Avg**	**3742**	**934**
Hwy 45	1	1300	338	1	3300	638
(1.81)	2	1350	325	2	3312	625
	3	1288	325	3	3300	550
	4	1438	350	4	3200	563
-23.3-	5	1425	363	5	3188	638
--9.6--	6	1425	350	6	3150	550
---13.7---	**Avg**	**1371**	**342**	**Avg**	**3242**	**594**
FR	1	2225	513	1	5475	825
(0.91)	2	2213	463	2	5475	825
	3	2225	475	3	5463	813
	4	2350	400	4	5287	775
-12.2-	5	2325	413	5	5300	775
--4.5--	6	2350	400	6	5300	775
---8.2---	**Avg**	**2281**	**444**	**Avg**	**5383**	**798**
FR	1	2125	438	1	5250	1100
(1.36)	2	2113	438	2	5275	1125
	3	2125	438	3	5250	1100
	4	1900	700	4	5287	1362
-17.8-	5	1888	688	5	5250	1375
--7.2--	6	1900	688	6	5262	1362
---10.6---	**Avg**	**2009**	**565**	**Avg**	**5262**	**1237**
FR	1	1438	350	1	4900	1138
(1.81)	2	1425	325	2	4800	1125
	3	1438	350	3	4825	1113
	4	1325	388	4	5013	925
-23.3-	5	1325	400	5	5000	913
--7.3--	6	1300	388	6	5013	925
---16.8---	**Avg**	**1375**	**367**	**Avg**	**4925**	**1023**

-Value- indicates grams of fully cured emulsion in SCR specimens.
--Value-- indicates grams of fully cured emulsion removed from SCR specimens.
---Value--- indicates grams of fully cured emulsion remaining in SCR Specimens.

Table A.7

Viscosity Characteristics of Pavements with Emulsion 5 Applied (6.3 mm)

Pavement Type (Application Rate) (L/m^2)		**Viscosity at 6.3 mm (cP)** *SCR* **Reading**	**135 C**	**165 C**
Hwy 45		1	2675	638
(0.91)		2	2675	638
		3	2688	638
		4	2575	625
	-12.0-	5	2575	625
	--4.3--	6	2588	625
	---7.7---	**Avg**	**2629**	**632**
Hwy 45		1	2225	638
(1.36)		2	2225	638
		3	2225	638
		4	2875	638
	-17.5-	5	2875	650
	--5.5--	6	2863	650
	---12.0---	**Avg**	**2548**	**642**
Hwy 45		1	2588	588
(1.81)		2	2575	588
		3	2588	600
		4	2400	550
	-22.9-	5	2413	550
	--10.0--	6	2413	538
	---12.9---	**Avg**	**2496**	**569**
FR		1	2825	675
(0.91)		2	2813	663
		3	2825	675
		4	2525	563
	-12.0-	5	2513	563
	--3.9--	6	2525	563
	---8.1---	**Avg**	**2671**	**617**
FR		1	2225	513
(1.36)		2	2225	513
		3	2225	525
		4	2412	525
	-17.5-	5	2425	525
	--8.1--	6	2425	538
	---9.4---	**Avg**	**2323**	**523**
FR		1	2125	500
(1.81)		2	2125	500
		3	2113	475
		4	2000	513
	-22.9-	5	2013	525
	--9.9--	6	2013	525
	---13.0---	**Avg**	**2064**	**506**

-Value- indicates grams of fully cured emulsion in SCR specimens.
--Value-- indicates grams of fully cured emulsion removed from SCR specimens.
---Value--- indicates grams of fully cured emulsion remaining in SCR Specimens.

Table A.8

Viscosity Characteristics of Pavements with Emulsion 6 Applied (6.3 mm)

Pavement Type (Application Rate) (L/m^2)		**Viscosity at 6.3 mm (cP)** ***SCR***		
		Reading	**135 C**	**165 C**
Hwy 45		1	4425	850
(0.91)		2	4425	863
		3	4413	888
		4	4188	888
	-12.4-	5	4213	875
	--4.7--	6	4213	863
	---7.7---	**Avg**	**4313**	**871**
Hwy 45		1	3938	850
(1.36)		2	3925	863
		3	3925	863
		4	3913	888
	-18.0-	5	3925	888
	--6.4--	6	3913	875
	---11.6---	**Avg**	**3923**	**871**
Hwy 45		1	3675	800
(1.81)		2	3688	800
		3	3663	800
		4	3725	888
	-23.6-	5	3713	888
	--8.6--	6	3713	875
	---15.0---	**Avg**	**3696**	**842**
FR		1	4438	950
(0.91)		2	4413	963
		3	4413	963
		4	4488	913
	-12.4-	5	4500	888
	--4.2--	6	4488	888
	---8.2---	**Avg**	**4457**	**928**
FR		1	4225	813
(1.36)		2	4213	825
		3	4225	825
		4	4050	875
	-18.0-	5	4063	863
	--7.7--	6	4050	838
	---10.3---	**Avg**	**4138**	**840**
FR		1	4288	800
(1.81)		2	4275	813
		3	4275	813
		4	4275	800
	-23.6-	5	4288	800
	--11.2--	6	4288	813
	---12.4---	**Avg**	**4282**	**807**

-Value- indicates grams of fully cured emulsion in SCR specimens.
--Value-- indicates grams of fully cured emulsion removed from SCR specimens.
---Value--- indicates grams of fully cured emulsion remaining in SCR Specimens.

Table A.9

Viscosity Characteristics of Pavements with Emulsion 7 Applied (6.3 mm)

Pavement Type (Application Rate) (L/m^2)	**Viscosity at 6.3 mm (cP)** *SCR* **Reading**	**135 C**	**165 C**
Hwy 45	1	3738	863
(0.91)	2	3750	863
	3	3750	863
	4	3650	738
-12.6-	5	3625	738
--3.1--	6	3625	750
---9.5---	**Avg**	**3690**	**803**
Hwy 45	1	3388	738
(1.36)	2	3388	738
	3	3375	725
	4	3225	663
-18.4-	5	3225	675
--8.5--	6	3225	675
---9.9---	**Avg**	**3304**	**702**
Hwy 45	1	3112	650
(1.81)	2	3112	650
	3	3100	650
	4	3050	625
-24.4-	5	3063	625
--10.4--	6	3050	638
---13.7---	**Avg**	**3081**	**640**
FR	1	4200	1288
(0.91)	2	4200	1275
	3	4225	1275
	4	4163	1000
-12.6-	5	4175	1000
--3.6--	6	4163	988
---9.1---	**Avg**	**4188**	**1138**
FR	1	4200	925
(1.36)	2	4187	925
	3	4187	913
	4	4150	1075
-18.4-	5	4163	1063
--7.4--	6	4150	1063
---11.0---	**Avg**	**4173**	**994**
FR	1	3300	863
(1.81)	2	3263	863
	3	3275	875
	4	3463	1000
-24.4-	5	3475	1000
--9.6--	6	3475	987
---14.5---	**Avg**	**3375**	**931**

-Value- indicates grams of fully cured emulsion in SCR specimens.
--Value-- indicates grams of fully cured emulsion removed from SCR specimens.
---Value--- indicates grams of fully cured emulsion remaining in SCR Specimens.

Table A.10

Viscosity Data of Highway 17 (Carroll County, MS)

Location	**Seal**	**Core Thickness (mm)**	**Viscosity at 135 C (cP)**	**Extraction (%)**
5.061	Scrub	86	4425	7.1
5.156		70	4387	
			4412	
			4408	
5.251	Scrub	81	5975	7.4
5.346		45	5975	
			5950	
			5967	
5.751	Chip	78	5512	4.6
6.251		92	5537	
			5537	
			5529	
6.751	Chip	65	5838	5.0
7.251			5800	
			5825	
			5821	
7.656	None	55	7325	5.5
7.751		75	7350	
			7338	
			7338	
7.846	None	70	6637	5.2
7.880		95	6637	
			6650	
			6641	
7.881	None	92	6838	5.7
7.879		92	6825	
			6888	
			6850	

At each coordinate, one core was obtained. Two cores close to each other were combined for extraction-recovery-viscosity tests. The top 6.3 mm was sliced for each core and tested. Specimens were scraped (i.e. SCR).

Table A.11

Viscosity Characteristics of Fully Cured Emulsion

	Test No	Viscosity (cP) of Emulsion Residue[1]						
		Emulsion 1	**Emulsion 2**	**Emulsion 3**	**Emulsion 4**	**Emulsion 5**	**Emulsion 6**	**Emulsion 7**
PVC Rings Section 3.7.2	1	1438	2313	1563	1050	1237	1663	4275
	2	1438	2300	1563	1050	1225	1675	4275
	3	1438	2313	1575	1038	1225	1675	4275
	4	1475	2362	1550	1075	1250	1750	--
	5	1475	2375	1550	1063	1250	1712	--
	6	1463	2362	1538	1063	1263	1750	--
	Avg	**1455**	**2338**	**1557**	**1057**	**1242**	**1704**	**4275**
Moisture Tin Section 3.7.3	1	1400	1825	1913	1300	1188	1587	4500
	2	1388	1825	1925	1300	1175	1600	4513
	3	1388	1838	1925	1288	1188	1600	4500
	4	1325	1838	1825	1325	--	1600	--
	5	1313	1850	1850	1275	--	1600	--
	6	1325	1850	1850	1275	--	1613	--
	Avg	**1357**	**1838**	**1881**	**1294**	**1184**	**1600**	**4504**
	Avg[2]	**1406**	**2088**	**1719**	**1173**	**1213**	**1652**	**4389**

1: Test was conducted at 135 C.
2: Averaged value for cured emulsion with combined methods.

APPENDIX B

EXTRACTION TEST DATA

Table B.1

Extraction Characteristics with No Emulsion

Pavement Type	Depth of Cut (mm)	Method	Extraction (%)
Hwy 45	6.3	*NS*	4.3
	6.3	*NS*	5.1
	6.3	*NS*	5.3
	6.3	*NS*	5.1
	6.3	*NS*	4.9
	9.5	*NS*	4.9
	9.5	*NS*	5.2
	12.5	*NS*	4.8
	12.5	*NS*	6.2
FR	6.3	*NS*	6.1
	6.3	*NS*	4.7
	6.3	*NS*	5.7
	6.3	*NS*	5.3
	6.3	*NS*	5.4
	9.5	*NS*	5.5
	9.5	*NS*	5.5
	12.5	*NS*	5.2
	12.5	*NS*	5.1

Table B.2

Characteristics with Emulsions 1 and 2 (6.3 mm)

Emulsion No.	Pavement Type	Application Rate (L/m^2)	Method[1]	Extraction (%)
1	*Hwy 45*	0.91	*NS*	7.9
1	*Hwy 45*	0.91	*NS*	7.6
1	*Hwy 45*	0.91	*SCR*	13.7
1	*Hwy 45*	0.91	*SCR*	9.1
1	*Hwy 45*	1.36	*NS*	9.7
1	*Hwy 45*	1.36	*NS*	10.0
1	*Hwy 45*	1.36	*SCR*	8.2
1	*Hwy 45*	1.36	*SCR*	6.5
1	*Hwy 45*	1.81	*NS*	11.0
1	*Hwy 45*	1.81	*NS*	12.0
1	*Hwy 45*	1.81	*SCR*	6.9
1	*Hwy 45*	1.81	*SCR*	7.6
1	*FR*	0.91	*NS*	9.9
1	*FR*	0.91	*NS*	9.7
1	*FR*	0.91	*SCR*	8.4
1	*FR*	0.91	*SCR*	7.9
1	*FR*	1.36	*NS*	12.7
1	*FR*	1.36	*NS*	14.8
1	*FR*	1.36	*SCR*	8.1
1	*FR*	1.36	*SCR*	9.7
1	*FR*	1.81	*NS*	12.3
1	*FR*	1.81	*NS*	12.5
1	*FR*	1.81	*SCR*	9.1
1	*FR*	1.81	*SCR*	8.5
2	*Hwy 45*	0.91	*NS*	9.0
2	*Hwy 45*	0.91	*NS*	9.2
2	*Hwy 45*	0.91	*SCR*	6.8
2	*Hwy 45*	0.91	*SCR*	8.5
2	*Hwy 45*	1.36	*NS*	10.5
2	*Hwy 45*	1.36	*NS*	--
2	*Hwy 45*	1.36	*SCR*	10.7
2	*Hwy 45*	1.36	*SCR*	8.2
2	*Hwy 45*	1.81	*NS*	10.1
2	*Hwy 45*	1.81	*NS*	10.0
2	*Hwy 45*	1.81	*SCR*	6.6
2	*Hwy 45*	1.81	*SCR*	8.7
2	*FR*	0.91	*NS*	10.2
2	*FR*	0.91	*NS*	9.6
2	*FR*	0.91	*SCR*	8.7
2	*FR*	0.91	*SCR*	7.4
2	*FR*	1.36	*NS*	10.3
2	*FR*	1.36	*NS*	10.3
2	*FR*	1.36	*SCR*	8.1
2	*FR*	1.36	*SCR*	9.4
2	*FR*	1.81	*NS*	12.3
2	*FR*	1.81	*NS*	12.4

[1] *Either Scraped (SCR) or Non Scraped (NS) specimens*

Table B.3

Extraction Characteristics with Emulsions 2 through 4 (6.3 mm)

Emulsion No.	Pavement Type	Application Rate (L/m^2)	Method[1]	Extraction (%)
2	*FR*	1.81	*SCR*	7.6
2	*FR*	1.81	*SCR*	5.5
3	*Hwy 45*	0.91	*NS*	7.2
3	*Hwy 45*	0.91	*NS*	6.3
3	*Hwy 45*	0.91	*SCR*	7.8
3	*Hwy 45*	0.91	*SCR*	9.9
3	*Hwy 45*	1.36	*NS*	8.3
3	*Hwy 45*	1.36	*NS*	8.4
3	*Hwy 45*	1.36	*SCR*	13.0
3	*Hwy 45*	1.36	*SCR*	6.9
3	*Hwy 45*	1.81	*NS*	9.2
3	*Hwy 45*	1.81	*NS*	8.0
3	*Hwy 45*	1.81	*SCR*	7.3
3	*Hwy 45*	1.81	*SCR*	9.4
3	*FR*	0.91	*NS*	8.5
3	*FR*	0.91	*NS*	9.7
3	*FR*	0.91	*SCR*	8.0
3	*FR*	0.91	*SCR*	6.7
3	*FR*	1.36	*NS*	8.9
3	*FR*	1.36	*NS*	9.3
3	*FR*	1.36	*SCR*	9.7
3	*FR*	1.36	*SCR*	7.8
3	*FR*	1.81	*NS*	9.7
3	*FR*	1.81	*NS*	9.8
3	*FR*	1.81	*SCR*	13.4
3	*FR*	1.81	*SCR*	13.5
4	*Hwy 45*	0.91	*NS*	5.2
4	*Hwy 45*	0.91	*NS*	8.2
4	*Hwy 45*	0.91	*SCR*	--
4	*Hwy 45*	0.91	*SCR*	--
4	*Hwy 45*	1.36	*NS*	7.1
4	*Hwy 45*	1.36	*NS*	8.9
4	*Hwy 45*	1.36	*SCR*	7.6
4	*Hwy 45*	1.36	*SCR*	--
4	*Hwy 45*	1.81	*NS*	7.2
4	*Hwy 45*	1.81	*NS*	6.1
4	*Hwy 45*	1.81	*SCR*	6.8
4	*Hwy 45*	1.81	*SCR*	--
4	*FR*	0.91	*NS*	9.6
4	*FR*	0.91	*NS*	8.4
4	*FR*	0.91	*SCR*	7.4
4	*FR*	0.91	*SCR*	--
4	*FR*	1.36	*NS*	9.7
4	*FR*	1.36	*NS*	10.5
4	*FR*	1.36	*SCR*	7.8
4	*FR*	1.36	*SCR*	--

[1] *Either Scraped (SCR) or Non Scraped (NS) specimens*

Table B.4

Extraction Characteristics with Emulsions 4 through 7 (6.3 mm)

Emulsion No.	Pavement Type	Application Rate (L/m^2)	Method[1]	Extraction (%)
4	*FR*	1.81	*NS*	9.8
4	*FR*	1.81	*NS*	--
4	*FR*	1.81	*SCR*	7.1
4	*FR*	1.81	*SCR*	--
5	*Hwy 45*	0.91	*SCR*	5.8
5	*Hwy 45*	0.91	*SCR*	--
5	*Hwy 45*	1.36	*SCR*	6.5
5	*Hwy 45*	1.36	*SCR*	--
5	*Hwy 45*	1.81	*SCR*	6.9
5	*Hwy 45*	1.81	*SCR*	--
5	*FR*	0.91	*SCR*	5.7
5	*FR*	0.91	*SCR*	--
5	*FR*	1.36	*SCR*	6.8
5	*FR*	1.36	*SCR*	--
5	*FR*	1.81	*SCR*	7.8
5	*FR*	1.81	*SCR*	--
6	*Hwy 45*	0.91	*SCR*	6.3
6	*Hwy 45*	0.91	*SCR*	6.6
6	*Hwy 45*	1.36	*SCR*	7.0
6	*Hwy 45*	1.36	*SCR*	7.0
6	*Hwy 45*	1.81	*SCR*	7.4
6	*Hwy 45*	1.81	*SCR*	7.9
6	*FR*	0.91	*SCR*	7.6
6	*FR*	0.91	*SCR*	7.8
6	*FR*	1.36	*SCR*	7.6
6	*FR*	1.36	*SCR*	8.2
6	*FR*	1.81	*SCR*	7.7
6	*FR*	1.81	*SCR*	9.5
7	*Hwy 45*	0.91	*SCR*	6.5
7	*Hwy 45*	0.91	*SCR*	--
7	*Hwy 45*	1.36	*SCR*	7.7
7	*Hwy 45*	1.36	*SCR*	--
7	*Hwy 45*	1.81	*SCR*	7.5
7	*Hwy 45*	1.81	*SCR*	--
7	*FR*	0.91	*SCR*	7.0
7	*FR*	0.91	*SCR*	--
7	*FR*	1.36	*SCR*	8.4
7	*FR*	1.36	*SCR*	--
7	*FR*	1.81	*SCR*	8.8
7	*FR*	1.81	*SCR*	--

[1] *Either Scraped (SCR) or Non Scraped (NS) specimens*

Table B.5

Extraction Characteristics with Emulsion 3

Pavement Type	Application Rate (L/m^2)	Depth of Cut (mm)	Method[1]	Extraction (%)
FR	0.91	9.5	*NS*	9.7
FR	0.91	9.5	*NS*	9.4
FR	0.91	12.5	*NS*	7.2
FR	0.91	12.5	*NS*	8.3
FR	1.36	9.5	*NS*	8.8
FR	1.36	9.5	*NS*	8.2
FR	1.36	12.5	*NS*	8.8
FR	1.36	12.5	*NS*	8.4

[1] *Non Scraped (NS) specimens*

APPENDIX C

FROSTED MARBLE TEST DATA

Table C.1

Frosted Marble Test Using Emulsion 1

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	3*	15*	6*	9*	48*	6*	6*	9*	6*	6*	12*	24*	12*
2	6*	18*	6*	21*	30*	6*	6*	9*	6*	6*	27*	12*	27*
3	6	12	6*	15	30*	27*	6*	21*	6*	9	18	15	15
4	6	12	6*	12	9	9	33*	27*	9*	21*	15	18	21
5	6	9	6*	12	18	9	9	15	18	18	15	15	18
6	6	9	18	9	24	9	9	18	15	15	15	12	12
7	6	9	9	12	6	9	24	15	18	15	15	15	12
8	6	15	12	15	18	12	18	15	21	18	21	12	15
9	6	12	12	12	15	15	12	18	12	18	12	18	15
10	9	9	9	12	15	15	9	15	15	12	15	12	15
11	9	9	12	15	15	18	15	15	15	15	15	15	18
12	9	12	9	12	15	18	18	18	12	18	15	21	18
13	9	9	9	15	15	21	18	15	18	21*	15	18	15
14	18	12	12	15	9	21	18	9	18	15	15	12	12
15	18	15	12	12	9	15	12	15	9	21	15	18	18
Avg	**8.8**	**11.1**	**11.4**	**12.9**	**14.0**	**14.3**	**14.7**	**15.3**	**15.5**	**15.8**	**15.5**	**15.5**	**15.7**

* *This denotes that this value was removed from calculations based on an engineer's judgment. The units for this test were kg-cm.*

Table C.2

Frosted Marble Test Using Emulsion 2

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	3*	63*	6*	33*	27*	33*	9*	6*	3*	24*	30*	33*	36*
2	3*	30*	6*	21*	21*	21*	9*	12*	6*	24*	15*	15*	15*
3	3*	27*	6*	6*	6*	9*	6*	15	9	15	15	15	21
4	3*	24*	6*	9*	6*	9*	9	12	9	18	18	15	18
5	3*	24*	6*	15	15	9	9	18	9	15	15	21	30
6	6	9	15	12	15	18	9	15	12	18	18	18	27
7	6	15	12	9	12	18	12	12	12	18	18	21	21
8	9	9	12	9	18	18	12	18	12	18	18	15	15
9	6	15	15	15	21	18	15	12	15	18	18	18	18
10	15	21	9	9	21	12	15	15	15	18	15	24	27
11	9	12	15	15	12	12	18	18	15	12	24	15	21
12	6	15	18	18	12	18	18	18	18	15	15	18	18
13	6	15	18	15	15	12	18	18	21	15	18	18	15
14	6	18	15	15	9	12	21	12	24	21	18	18	15
15	9	9	9	21	12	21	24	15	24	18	15	18	18
Avg	**7.8**	**13.8**	**13.8**	**13.9**	**14.7**	**15.3**	**15**	**15.2**	**15.0**	**16.8**	**17.3**	**18.0**	**20.3**

* *This denotes that this value was removed from calculations based on an engineer's judgment. The units for this test were kg-cm.*

Table C.3

Frosted Marble Test Using Emulsion 3

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	24*	60*	6*	21*	48*	27*	6*	27*	6*	6*	21*	30*	12*
2	6*	24*	6*	6*	30*	6*	6*	27*	6*	9*	12	12*	12*
3	12	24*	6*	9	30*	6*	6*	9*	6*	9*	15	15	12
4	15	9	6*	9	9	9*	33*	12	9*	12	18	15	15
5	9	12	9	12	15	12	9	18	18	15	15	9	12
6	15	9	9	12	24	15	18	18	12	15	15	15	15
7	9	18	15	12	18	15	9	12	18	15	18	15	15
8	12	15	15	15	15	9	9	15	18	18	12	15	18
9	6	15	15	15	15	21	12	18	9	15	9*	18	15
10	9	9	9	15	9	21	18	12	18	18	15	12	15
11	12	9	15	15	6	18	15	9	12	12	15	18	18
12	12	15	15	15	15	9	12	18	18	18	18	18	18
13	9	15	15	18	9	9	18	12	18	18	12	12	15
14	12	15	18	9	15	9	18	12	12	15	15	18	15
15	12	12	9	18	9	18	18	24	12	12	15	18	18
Avg	**11.1**	**12.8**	**13.1**	**13.4**	**13.3**	**14.2**	**14.2**	**15.0**	**15.0**	**15.3**	**15.0**	**15.2**	**15.5**

** This denotes that this value was removed from calculations based on an engineer's judgment. The units for this test were kg-cm.*

Table C.4

Frosted Marble Test Using Emulsion 4

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	21*	36*	24*	24*	33*	6*	6*	9*	21*	21*	21*	33*	27*
2	27*	27*	21*	6*	27*	6*	6*	6*	24*	24*	12*	15*	15*
3	12	6*	15	6*	3*	6*	6*	21*	12*	12*	18	18	18
4	12	9*	15	9*	6	12	9	21	9*	9*	12	15	18
5	6	12	12	21	15	12	9	9	15	15	21	15	18
6	12	12	15	18	9	12	12	9	15	15	21	18	21
7	15	15	9	15	9	12	30	12	18	18	21	18	21
8	15	15	15	12	18	30	18	15	21	21	15	30	18
9	18	12	18	9	15	9	9	9	12	12	15	30	21
10	15	12	15	9	18	18	21	18	15	15	21	15	15
11	15	9	15	15	18	9	18	18	12	21	18	15	21
12	6	15	12	15	12	18	18	18	15	12	21	15	24
13	9	15	15	18	18	12	9	18	21	18	18	18	21
14	15	9	18	18	24	15	15	18	12	12	12	18	18
15	15	18	15	9	12	18	12	18	18	15	15	21	21
Avg	**12.7**	**13.1**	**14.5**	**14.5**	**14.5**	**14.8**	**15.0**	**15.3**	**15.8**	**15.8**	**17.5**	**18.9**	**19.6**

** This denotes that this value was removed from calculations based on an engineer's judgment. The units for this test were kg-cm.*

Table C.5

Frosted Marble Test Using Emulsion 5

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	3*	18*	21*	12*	33*	36*	33*	45	24*	9*	27*	27*	21*
2	3*	18*	18*	12*	30*	12*	9*	6	6*	9*	12*	15*	12*
3	12	9*	15	15	6*	9*	15	15	12*	9*	15	18	15
4	9	6*	18	12	3*	15	15	18	21	9*	21	15	18
5	9	9	9	15	15	12	21	12	18	21	18	15	18
6	6	12	9	15	15	18	15	15	21	12	18	18	15
7	12	18	18	18	6	18	21	15	15	12	21	15	15
8	9	12	15	15	27	18	21	15	15	27	15	27	18
9	9	12	15	12	15	12	12	15	15	18	15	15	18
10	9	15	15	15	15	12	12	18	12	15	15	18	21
11	6	9	15	15	18	18	12	18	12	18	18	15	18
12	6	9	18	15	18	9	12	12	15	15	15	18	18
13	12	12	15	15	12	12	15	15	15	12	15	18	18
14	6	15	15	18	15	18	15	18	15	12	15	15	18
15	6	15	15	12	18	18	15	18	15	12	15	15	21
Avg	**8.5**	**12.5**	**14.8**	**14.8**	**15.8**	**15.0**	**15.5**	**15.7**	**15.8**	**15.8**	**16.6**	**17.1**	**17.8**

** This denotes that this value was removed from calculations based on an engineer's judgment.*
The units for this test were kg-cm.

Table C.6

Frosted Marble Test Using Emulsion 6

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	6*	21*	6*	3*	27*	33*	12*	6*	6*	6*	21*	24*	36*
2	6*	21*	6*	3*	27*	33*	15	6*	6*	6*	21*	12*	12*
3	9	27*	9	6*	27*	12*	9	9	15	9*	15	18	18
4	6	18*	15	6	24*	9*	24	12	15	9*	12	15	15
5	6	9	12	9	30*	21	12	12	15	15	15	15	21
6	9	15	12	12	15	18	12	15	15	12	15	15	18
7	6	15	15	15	15	18	12	15	15	9	18	18	18
8	12	12	12	12	15	18	21	15	15	12	18	15	21
9	9	15	12	12	15	15	27	12	18	9	18	12	18
10	12	15	15	18	15	18	15	18	15	15	18	18	18
11	6	12	15	6	15	12	12	15	18	27	18	15	18
12	6	9	6	12	12	12	21	15	18	18	18	18	21
13	6	12	9	12	15	18	12	18	15	18	9	12	18
14	6	6	9	6	18	18	15	15	18	15	12	15	18
15	12	9	12	6	18	21	12	12	15	15	15	15	18
Avg	**8.1**	**11.7**	**11.8**	**10.5**	**15.3**	**17.1**	**15.6**	**14.1**	**15.9**	**15.0**	**15.5**	**15.5**	**18.5**

** This denotes that this value was removed from calculations based on an engineer's judgment.*
The units for this test were kg-cm.

Table C.7

Frosted Marble Test Using Emulsion 6 (Performed by Operator 2)

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	21*	18*	15	30*	15	27*	12*	18	30*	36*	30*	36*	27*
2	9*	24*	15	15	15	15	12*	18	15	15	30*	18	27*
3	9*	9	15	15	18	15	21	15	15	21	15	21	30*
4	24*	9	15	15	15	18	18	24	15	18	18	18	21
5	12	18	12	15	18	18	15	18	18	18	18	21	24
6	12	9	18	12	21	18	24	15	18	18	18	18	24
7	12	9	15	12	18	21	27	18	18	21	15	18	21
8	12	9	15	15	24	18	15	18	21	18	15	27	18
9	15	12	18	18	24	18	21	18	18	27	18	18	24
10	18	12	15	18	18	15	21	15	24	18	21	18	24
11	12	12	12	15	18	18	15	18	27	18	18	24	21
12	15	12	12	12	15	18	21	18	24	24	24	21	24
13	12	12	15	15	15	15	15	27	18	18	18	21	21
14	15	12	12	18	21	18	15	24	18	24	15	18	21
15	15	15	18	21	18	18	18	18	15	18	15	21	24
Avg	**13.6**	**11.5**	**14.8**	**15.4**	**18.2**	**17.1**	**18.9**	**18.8**	**18.9**	**19.7**	**17.5**	**20.1**	**22.3**

** This denotes that this value was removed from calculations based on an engineer's judgment.*
Note: The operator was involved with the FMT at PTSI and was aware of the experimental program of this thesis. The units for this test were kg-cm.

Table C.8

Frosted Marble Test Using Emulsion 7

	Cure Time (Hours)												
Replicate	**0.5**	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	3*	21*	6*	27*	60*	33*	9*	27*	33*	33*	24*	27*	27*
2	3*	18*	6*	12*	33*	33*	6*	21*	6*	33*	15*	15*	15*
3	3*	9	6*	18	33*	9*	15	15	6*	12*	21*	18	21
4	12	9	9	12	30*	9	12	18	6*	12	18	18	21
5	6	12	9	12	30*	15	12	18	12	12	18	21	18
6	6	18	15	12	21	15	15	18	12	15	18	15	24
7	6	12	15	12	9	18	12	15	18	18	18	21	18
8	6	12	9	12	15	21	15	12	18	21	15	18	18
9	6	15	12	12	24	21	15	15	15	15	15	21	18
10	6	12	12	18	15	18	12	15	15	15	21	24	18
11	18	15	12	15	15	18	9	18	18	9	18	18	21
12	6	15	15	12	15	12	15	15	15	18	15	18	21
13	6	15	15	12	15	12	21	15	18	21	21	21	21
14	9	15	18	12	15	15	21	15	15	21	18	24	21
15	9	12	18	15	9	15	24	15	15	24	21	15	18
Avg	**8.0**	**13.2**	**13.3**	**13.4**	**15.3**	**15.8**	**15.2**	**15.7**	**15.5**	**16.8**	**18.0**	**19.4**	**19.8**

** This denotes that this value was removed from calculations based on an engineer's judgment.*
The units for this test were kg-cm.

Table C.9

Frosted Marble Test Using Emulsion 8

Data Rep	Test Rep	Cure Time (Hours)												
		0.5	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	1	12*	21*	15*	15*	21*	18*	18*	15*	18*	30*	18*	30*	33*
	2	12*	18*	18*	15*	21*	18*	18*	18*	18*	30*	18*	30*	30*
	3	21*	15*	18*	18*	18*	18*	24*	21*	27*	18*	30*	18*	27*
	4	18*	12*	15*	18*	18*	18*	27*	21*	24*	18*	33*	18*	21*
	5	15	15	18	18	18	18	18	21	21	21	24	21	27
	6	15	15	18	18	18	18	18	18	21	24	24	30	30
	7	15	15	15	18	21	18	18	18	24	21	18	30	30
	8	15	15	15	18	18	18	18	18	24	21	18	27	30
	9	18	15	15	18	18	18	21	18	24	21	24	21	30
	10	15	15	18	18	18	18	21	18	18	24	24	30	30
	11	18	15	15	15	18	18	21	21	21	21	21	30	30
	12	15	15	18	15	18	18	21	21	18	18	21	30	30
	13	15	15	15	18	18	18	21	18	21	18	21	18	30
	14	18	18	15	18	18	18	18	18	18	27	30	30	30
	15	12	18	15	18	18	18	18	18	24	27	21	30	27
	Avg	**15.5**	**15.5**	**16.1**	**17.5**	**18.3**	**18.0**	**19.4**	**18.8**	**21.3**	**22.1**	**22.4**	**27.0**	**29.5**
2	1	15*	9*	15*	15*	21*	30*	18*	15*	30*	24*	18*	30*	39*
	2	15*	12*	18*	15*	21*	24*	15*	18*	30*	27*	18*	21*	39*
	3	21*	18*	15*	18*	15*	18*	24*	24*	18*	18*	30*	45*	27*
	4	21*	18*	18*	18*	15*	15*	30*	24*	18*	15*	30*	18*	27*
	5	15	12	15	18	15	18	21	21	18	21	24	30	30
	6	15	15	15	15	18	18	21	18	18	24	21	27	30
	7	18	15	15	18	18	21	18	18	21	24	27	27	30
	8	15	15	15	18	18	21	21	18	21	21	21	21	30
	9	21	15	15	18	18	18	15	21	24	21	24	27	36
	10	15	18	18	18	18	18	18	21	24	18	24	30	30
	11	15	15	18	18	18	18	18	18	21	21	21	30	30
	12	18	15	15	15	15	18	21	18	21	21	18	30	30
	13	15	12	15	18	18	21	21	24	21	21	21	24	30
	14	18	15	15	18	18	18	18	24	27	21	24	24	27
	15	15	15	15	15	18	18	18	18	18	21	24	21	30
	Avg	**16.4**	**14.7**	**15.5**	**17.2**	**17.5**	**18.8**	**19.1**	**19.9**	**21.3**	**21.3**	**22.6**	**26.5**	**30.3**
3	1	21	12	15*	18*	27*	15*	30*	15*	21*	18*	18*	30*	33
	2	21	18	15*	18*	15*	18*	30*	15*	18*	18*	18*	18*	30
	3	15	18	18*	15*	15*	30*	18*	27*	21*	24*	30*	18*	21
	4	12	12	18*	15*	18*	24*	15*	24*	18*	24*	30*	30*	27
	5	18	15	15	18	18	18	21	18	18	21	24	21	27
	6	18	15	15	18	18	18	18	21	21	24	21	27	27
	7	15	12	15	15	15	21	18	18	21	21	21	24	27
	8	18	15	15	18	18	18	30	15	18	24	24	27	27
	9	18	18	15	15	18	21	27	18	21	24	24	24	30
	10	18	15	15	18	15	18	18	18	18	21	24	21	30
	11	18	15	15	18	15	21	21	18	18	21	24	18	21
	12	15	15	15	15	15	18	18	24	18	21	21	24	30
	13	15	15	15	15	18	18	18	18	18	21	21	21	30
	14	18	15	15	15	15	18	18	18	21	24	24	27	27
	15	18	15	15	18	15	18	18	18	21	21	24	18	27
	Avg	**17.2**	**15.0**	**15.0**	**16.6**	**16.4**	**18.8**	**20.5**	**18.5**	**19.4**	**22.1**	**22.9**	**22.9**	**27.5**
Avg^A	--	**16.4**	**15.2**	**15.5**	**17.1**	**17.4**	**18.5**	**19.6**	**19.1**	**20.6**	**21.8**	**22.6**	**25.5**	**29.1**
Avg^B	--	**16.5**	**15.1**	**15.8**	**16.9**	**17.7**	**19.1**	**20.3**	**19.3**	**20.9**	**21.9**	**23.1**	**25.5**	**29.2**

A: is the averaged value with data (2 highest and 2 lowest points) taken out
B: is the averaged value with all data point
The units are in kg-cm.

Table C.10

Frosted Marble Test Using Emulsion 9

Data Rep	**Test Rep**	**Cure Time (Hours)**												
		0.5	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	1	9*	15*	12*	18*	21*	21*	18*	30*	30*	30*	30*	15*	30*
	2	12*	15*	18*	18*	15*	27*	15*	27*	30*	30*	30*	30*	30*
	3	15*	12*	15*	15*	15*	15*	27*	18*	15*	21*	18*	15*	21*
	4	15*	12*	12*	15*	21*	15*	21*	18*	21*	21*	18*	30*	21*
	5	12	15	12	15	18	18	18	18	24	27	24	18	21
	6	15	15	15	15	18	18	18	24	27	24	21	18	24
	7	15	15	15	15	18	18	21	18	27	21	27	27	27
	8	15	12	15	15	18	21	21	18	18	21	27	18	27
	9	15	12	15	15	18	24	18	24	21	21	24	27	30
	10	12	15	15	15	18	18	18	21	30	21	27	24	21
	11	12	15	15	15	18	18	18	21	21	24	27	24	24
	12	12	15	15	15	18	15	21	21	21	24	27	30	21
	13	12	15	15	15	18	21	21	27	21	24	27	27	21
	14	15	15	15	15	15	18	18	18	24	24	30	27	27
	15	15	15	15	15	15	18	18	18	30	24	21	30	27
	Avg	**13.6**	**14.5**	**14.7**	**15**	**17.5**	**18.8**	**19.1**	**20.7**	**24**	**23.2**	**25.6**	**24.5**	**24.5**
2	1	9*	12*	12*	12*	15*	15*	15*	30*	30*	30*	30*	15*	21
	2	12*	12*	15*	12*	21*	15*	15*	30*	27*	30*	30*	18*	21
	3	15*	18*	18*	18*	21*	21*	27*	15*	15*	15*	18*	27*	27
	4	15*	18*	18*	18*	15*	24*	27*	18*	18*	18*	18*	27*	27
	5	15	12	18	15	18	18	18	18	24	27	21	21	21
	6	12	15	15	18	18	21	18	21	24	27	24	24	24
	7	15	15	18	18	15	21	21	27	24	21	24	24	24
	8	15	15	18	18	15	21	27	18	18	21	21	24	21
	9	12	15	15	18	15	18	18	27	21	21	24	27	27
	10	15	15	15	18	15	18	15	27	18	21	21	24	21
	11	15	15	15	18	21	18	21	24	21	24	24	18	21
	12	12	15	18	18	21	18	27	18	21	27	30	24	27
	13	12	15	15	18	18	18	27	18	27	18	24	24	21
	14	15	15	15	18	18	18	24	21	24	21	18	21	24
	15	15	15	15	18	21	18	18	21	21	21	21	27	21
	Avg	**13.9**	**14.7**	**16.1**	**17.7**	**17.7**	**18.8**	**21.3**	**21.8**	**22.1**	**22.6**	**22.9**	**23.5**	**22.9**
3	1	9*	12*	18*	18*	21*	15*	9*	21*	27*	15*	30*	30*	30*
	2	12*	12*	18*	18*	21*	15*	15*	21*	27*	24*	30*	30*	30*
	3	15*	15*	15*	15*	15*	18*	24*	15*	15*	15*	18*	18*	21*
	4	15*	15*	15*	15*	15*	21*	27*	18*	15*	24*	18*	18*	21*
	5	15	12	18	15	18	18	18	18	18	18	24	21	24
	6	15	12	15	15	18	15	24	18	21	18	27	30	21
	7	12	15	15	15	18	15	15	18	15	18	30	21	21
	8	12	15	15	15	15	18	15	18	18	18	27	21	21
	9	15	15	15	15	15	18	15	18	18	18	24	30	27
	10	12	15	15	18	18	18	18	18	15	21	24	21	27
	11	15	15	15	18	15	15	15	18	15	24	30	30	30
	12	15	15	15	18	15	18	18	18	18	21	30	21	30
	13	15	15	15	18	15	15	15	18	18	18	27	21	27
	14	12	15	15	18	15	15	15	18	21	18	18	21	27
	15	12	15	15	18	15	15	15	18	24	21	24	24	24
	Avg	**13.6**	**14.5**	**15.3**	**16.6**	**16.1**	**16.4**	**16.6**	**18**	**18.3**	**19.4**	**25.9**	**23.7**	**25.4**
Avg[A]	--	**13.7**	**14.5**	**15.4**	**16.5**	**17.1**	**18.0**	**19.0**	**20.2**	**21.5**	**21.7**	**24.8**	**23.9**	**24.3**
Avg[B]	--	**13.5**	**14.4**	**15.4**	**16.3**	**17.3**	**18.1**	**19.3**	**20.6**	**21.7**	**22.0**	**24.6**	**23.6**	**24.5**

A: is the averaged value with data (2 highest and 2 lowest points) taken out
B: is the averaged value with all data point

Table C.11

Frosted Marble Test Using Emulsion 10

Data Rep	Test Rep	Cure Time (Hours)												
		0.5	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
1	1	9*	12*	12*	18*	15*	21*	24*	18*	21*	18*	30*	24*	21*
	2	9*	12*	12*	18*	15*	21*	18*	18*	21*	27*	30*	24*	21*
	3	15*	12*	18*	15*	18*	15*	15*	15*	15*	36*	18*	18*	39*
	4	15*	12*	18*	12*	18*	15*	15*	15*	15*	15*	18*	18*	33*
	5	12	15	18	18	18	15	15	15	15	21	24	18	27
	6	12	15	15	18	15	15	15	18	21	21	27	21	27
	7	12	15	15	15	15	15	15	18	21	15	30	21	30
	8	15	15	15	15	18	15	18	18	18	21	21	21	24
	9	12	15	15	15	18	15	18	18	18	18	24	21	24
	10	12	12	15	15	18	18	18	18	18	18	27	18	27
	11	15	15	15	15	15	18	18	18	18	18	21	18	27
	12	15	15	15	18	18	18	18	18	18	27	18	24	27
	13	9	18	15	15	15	18	18	18	18	27	18	24	30
	14	15	15	15	18	18	18	18	18	18	21	18	21	30
	15	15	12	15	15	18	18	18	18	18	18	18	21	30
	Avg	**13.1**	**14.7**	**15.3**	**16.1**	**16.9**	**16.6**	**17.2**	**17.7**	**18.3**	**20.5**	**22.4**	**20.7**	**27.6**
2	1	9*	9*	12*	15*	15*	21*	21*	21*	15*	15*	15*	15*	30*
	2	9*	12*	18*	18*	15*	21*	21*	21*	15*	15*	18*	15*	21*
	3	18*	18*	18*	18*	21*	15*	15*	15*	21*	30*	27*	27*	39*
	4	18*	18*	12*	15*	18*	15*	15*	15*	27*	27*	27*	30*	33*
	5	12	15	15	18	18	15	15	15	18	21	21	21	27
	6	12	12	15	18	18	15	15	15	15	21	18	21	27
	7	9	15	15	18	18	15	15	15	18	27	21	15	21
	8	15	15	15	15	15	15	18	18	21	24	18	18	24
	9	15	12	15	15	15	18	18	18	21	21	18	18	24
	10	9	12	15	15	15	18	18	18	15	15	21	18	27
	11	15	15	15	15	15	18	18	18	15	21	18	24	27
	12	15	12	15	15	15	18	18	18	18	18	21	15	27
	13	15	12	15	15	15	18	18	18	21	27	27	24	30
	14	9	12	15	15	15	18	18	18	15	24	18	18	30
	15	12	15	12	15	15	18	18	18	18	24	21	18	30
	Avg	**12.6**	**13.4**	**14.7**	**15.8**	**15.8**	**16.9**	**17.2**	**17.2**	**17.7**	**22.1**	**20.2**	**19.1**	**26.7**
3	1	9*	9*	18*	18*	15*	15*	30*	21*	15*	18*	18*	30*	39*
	2	9*	12*	18*	12*	15*	15*	21*	21*	15*	18*	18*	30*	36*
	3	15*	15*	9*	12*	18*	21*	15*	15*	21*	27*	27*	15*	24*
	4	15*	15*	12*	21*	18*	21*	15*	15*	21*	30*	30*	15*	27*
	5	9	15	12	18	18	18	18	18	21	24	24	21	33
	6	15	15	18	15	15	15	18	15	15	15	15	18	33
	7	12	12	18	15	15	18	18	18	18	15	27	18	30
	8	15	15	18	15	15	15	18	18	18	27	24	27	33
	9	9	15	15	15	15	15	15	21	18	24	27	27	33
	10	15	15	15	15	15	18	15	15	18	27	15	30	27
	11	12	12	15	15	18	18	15	15	18	27	15	18	33
	12	15	12	15	15	18	18	15	18	18	27	15	15	30
	13	9	15	15	15	18	15	15	18	18	15	27	15	30
	14	9	15	15	15	18	15	21	18	18	15	27	15	30
	15	12	15	15	15	18	21	15	18	18	15	15	15	30
	Avg	**12.0**	**14.2**	**15.5**	**15.3**	**16.6**	**16.9**	**16.6**	**17.5**	**18.0**	**21.0**	**21.0**	**19.9**	**31.1**
Avg[A]	--	**12.5**	**14.1**	**15.2**	**15.7**	**16.5**	**16.8**	**17.0**	**17.5**	**18.0**	**21.2**	**21.2**	**19.7**	**28.5**
Avg[B]	--	**12.5**	**14.1**	**15.1**	**15.8**	**16.5**	**17.1**	**17.5**	**17.5**	**18.1**	**20.1**	**21.1**	**20.4**	**28.8**

A: is the averaged value with data (2 highest and 2 lowest points) taken out
B: is the averaged value with all data point
The units are in kg-cm.

APPENDIX D

EMULSION MOISTURE LOSS TEST DATA

Table D.1

Moisture Loss Tests Using FMT Trays

		wc_{LOSS}												
Emulsion (Water[1])	**Test**	**Cure Time at 57 C(hr)**												
		0.5	**1**	**1.5**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**24**	**48**	**120**
8	1	58.17	65.94	71.12	76.42	85.25	92.08	96.20	98.67	98.67	98.67	99.14	99.14	99.14
(0.311)	2	54.40	65.40	74.27	81.60	90.12	92.36	93.90	94.37	94.49	94.49	94.61	94.61	94.61
	Avg	**56.28**	**65.67**	**72.69**	**79.01**	**87.68**	**92.22**	**95.05**	**96.52**	**96.58**	**96.58**	**96.88**	**96.88**	**96.88**
9	1	58.93	64.13	72.48	75.40	83.20	88.83	91.00	92.73	92.95	93.06	94.68	94.68	94.68
(0.327)	2	60.75	62.29	73.49	88.21	88.54	88.87	89.86	91.29	91.84	92.17	93.37	93.37	93.37
	Avg	**59.84**	**63.21**	**72.98**	**81.81**	**85.87**	**88.85**	**90.43**	**92.01**	**92.39**	**92.61**	**94.03**	**94.03**	**94.03**
10	1	53.99	58.47	65.59	71.79	79.38	83.74	90.63	92.01	93.27	94.42	95.57	95.57	95.57
(0.319)	2	54.54	60.87	68.77	73.51	81.76	85.15	90.23	91.47	92.60	93.95	94.97	94.97	94.97
	Avg	**54.27**	**59.67**	**67.18**	**72.65**	**80.57**	**84.44**	**90.43**	**91.74**	**92.94**	**94.19**	**95.27**	**95.27**	**95.27**

1: Water Content of Emulsion (100 – Residue % (Found in Table 3.3))

Table D.2

Moisture Loss of Emulsion Using PVC Rings

Emulsion No.	Water (%)	Test No	wc_{LOSS} at Ambient Cure Time (hr)[1] 1	2	3	17	26	41	49	67	73	88	184
1	0.301	1	20.9	32.6	41.7	117.3	119.9	122.5	123.8	125.1	125.1	125.1	125.1
		2	19.5	30.0	33.9	114.7	116.0	118.6	121.2	121.2	121.2	121.2	121.2
2	0.319	1	1.2	11.1	16.0	79.9	83.6	84.8	88.5	88.5	88.5	88.5	88.5
		2	18.4	29.5	35.7	109.4	115.7	119.3	120.5	122.9	122.9	122.9	122.9
3	0.324	1	24.2	36.3	43.6	113.8	116.2	118.6	121.0	122.3	122.3	122.3	122.3
		2	31.5	44.8	50.8	113.8	116.2	117.4	119.8	121.0	122.3	122.3	122.3
4	0.303	1	22.1	35.1	40.3	106.5	113.0	113.0	114.3	116.9	116.9	116.9	116.9
		2	19.5	28.6	36.4	97.4	100.0	102.6	103.9	103.9	103.9	103.9	103.9
5	0.315	1	8.7	13.7	16.2	21.2	23.7	26.1	27.4	28.6	29.9	29.9	29.9
		2	22.4	32.4	37.4	58.5	63.5	67.2	67.2	68.5	69.7	69.7	69.7
6	0.293	1	24.1	36.1	41.5	99.0	101.7	104.4	107.1	109.8	111.1	111.1	111.1
		2	22.8	36.1	44.2	101.7	107.1	107.1	109.8	111.1	111.1	111.1	111.1
7	0.277	1	9.9	19.8	26.9	89.2	93.4	96.3	97.7	96.3	97.7	100.5	104.8
		2	22.7	39.6	42.5	117.5	123.2	127.4	128.8	131.7	133.1	131.7	145.8

1: Denotes Moisture Loss (%) at cure time.

Note: Emulsion had been in laboratory for extended period of time when this test was conducted. Residue value was conducted at original sampling of emulsion. Emulsions could have been too old at the time of these tests were conducted.

Table D.3

Moisture Loss of Emulsion using Moisture Tins

Emulsion	Water	Test	wc_{LOSS} at Cure Time (hrs)[1] Oven at 60° C												
No.	%	No	1	2	3	4	5	6	7	8	24	48	52	96	100
1	0.301	1	37.5	58.0	72.2	84.8	89.7	93.4	96.2	99.2	111.7	114.6	115.0	--	--
		2	34.6	52.8	64.8	75.7	79.9	83.2	85.6	88.2	99.2	101.9	102.2	--	--
2	0.319	1	20.7	28.2	34.8	43.7	48.6	53.2	57.3	62.5	108.8	139.8	--	153.3	153.3
		2	17.4	24.2	29.9	37.3	41.3	45.1	48.5	52.8	88.4	109.7	--	122.1	122.1
3	0.324	1	18.4	24.2	29.3	35.9	39.4	42.6	45.6	49.2	78.6	92.9	--	97.8	97.9
		2	17.0	22.5	27.3	33.5	36.7	39.7	42.4	45.7	71.4	82.7	--	86.2	86.3
4	0.303	1	20.3	27.0	32.7	39.9	43.7	47.2	50.6	54.6	84.8	96.9	--	100.7	100.8
		2	18.3	24.3	29.2	35.8	39.1	42.3	45.3	49.1	82.7	105.6	--	119.4	119.7
5	0.315	1	30.1	39.4	47.9	59.4	65.7	71.6	76.8	82.7	109.0	115.4	115.9	--	--
		2	24.7	32.8	40.0	49.9	55.2	60.2	64.6	69.7	94.8	101.7	102.3	--	--
6	0.293	1	12.5	17.4	21.2	26.8	30.1	33.1	36.0	39.8	73.8	94.5	--	104.0	104.3
		2	9.9	11.9	13.9	17.2	18.9	20.9	22.8	25.1	49.1	72.5	--	90.9	91.4
7	0.277	1	20.3	35.9	41.0	48.1	51.7	55.2	58.5	62.4	94.4	107.0	--	111.8	111.9
		2	17.4	20.4	26.8	33.1	36.4	39.6	42.5	46.4	75.8	87.6	--	104.8	105.0

1: Denotes Moisture Loss (%) at cure time.

Note: Emulsion had been in laboratory for extended period of time when this test was conducted. Residue value was conducted at original sampling of emulsion. Emulsions could have been too old at the time these tests were conducted.

APPENDIX E

PERMEABILITY TEST DATA

Table E.1

Permeability Data of Frontage Road (*FR*)

Core	Test No.	Height of Specimen (cm)	Diameter of Specimen (cm)	Time (seconds)	Area of Specimen (cm^2)	Permeability "k" at 20 C (cm^2/sec)
1	1	4.19	14.86	610	172.73	$122.1 * 10^{-5}$
	2	4.14	14.86	660		
	3	4.17	14.78	675		
	Avg	**4.17**	**14.83**	**648**		
2	1	4.17	14.81	907	173.43	$425.8 *10^{-6}$
	2	4.24	14.88	1784		
	3	4.24	14.88	2927		
	Avg	**4.22**	**14.86**	**1873**		
3	1	4.14	14.88	937	173.90	$318 * 10^{-6}$
	2	4.14	14.88	2296		
	3	4.14	14.88	4116		
	Avg	**4.14**	**14.88**	**2450**		
Avg Permeability						$657*10^{-6}$

Test temperature was approximately 22 C (temperature constant = 0.953).
Note: No emulsion was applied to these cores.

Table E.2

Permeability Data of Highway 45 (*Hwy 45*)

Core	Test No.	Height of Specimen (cm) (cm)	Diameter of Specimen (cm) (cm)	Time (Seconds) (seconds)	Area of Specimen (cm^2)	Permeability "k" at 20 C (cm^2/sec)
1	1	3.58	14.86	7200	172.73	$351.0 *10^{-10}$
	2	3.53	14.91	7200		
	3	3.48	14.73	7200		
	Avg	**3.53**	**14.83**	**7200**		
2	1	3.68	14.96	7200	172.96	$874.1 *10^{-8}$
	2	3.56	14.83	7200		
	3	3.56	14.73	7200		
	Avg	**3.60**	**14.84**	**7200**		
3	1	3.40	14.94	7200	174.37	$510.2 * 10^{-8}$
	2	3.40	15.01	7200		
	3	3.43	14.76	7200		
	Avg	**3.41**	**14.90**	**7200**		
Avg Permeability						$470*10^{-9}$

Test temperature was approximately 22 C (temperature constant = 0.953).
Note: No emulsion was applied to these cores.

Table E.3

Permeability Data of Highway 17 (Carroll County, Mississippi)

Location	Test No.	Height of Specimen (cm)	Diameter of Specimen (cm)	Time (Seconds)	Area of Specimen	Permeability “k” at 20 C
		(cm)	(cm)	(seconds)	(cm^2)	(cm^2/sec)
7.656	1	3.77	15.09	1592	178.79	190.9 * 10^{-2}
	2	3.59	15.08	786		
	3	3.71	15.10	1665		
	Avg	**3.68**	**15.09**	**1348**		
7.751	1	3.75	15.07	1655	178.22	172.1* 10^{-2}
	2	3.87	15.07	1488		
	3	3.84	15.07	1517		
	Avg	**3.82**	**15.07**	**1553**		

Test temperature was approximately 22 C (temperature constant = 0.953).
Note: No emulsion was applied to these cores.